White Paper:

The Effects of the Hells Canyon Complex Relative to Water Temperature and Fall Chinook Salmon.

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Table of Contents

List of Tables

List of Figures

Executive Summary

Several stakeholders interested in the relicensing by the Federal Energy Regulatory Commission (FERC) of the Hells Canyon Complex (HCC) have expressed concern over perceived downstream temperature impacts on fall Chinook salmon. For example, comments filed on FERC's draft environmental impact statement by the Environmental Protection Agency and others assert that the thermal shift associated with the HCC is deleterious to salmon at different life stages. The comments argue that installation of a temperature control structure in Brownlee Reservoir could ameliorate the hypothesized negative effects associated with this thermal shift by providing cooler conditions below the HCC in July and in the early fall, and therefore, FERC should require more investigation.

The temperature effects of the HCC are documented in the FERC License Application and in the application for certification under Clean Water Act § 401 filed before the Oregon and Idaho Departments of Environmental Quality. However, in response to the comments submitted to FERC, Idaho Power Company has prepared this White Paper, which comprehensively reviews and analyses HCC temperature effects against the literature and its own data gathered over many years. Our conclusion, based on the best available science, is that the temperature effects of the HCC are benign or beneficial to fall Chinook salmon. Specifically, the White Paper finds:

1. Significant anthropogenic influences on water temperature have occurred in the Snake River basin both upstream of Hells Canyon Dam and as a result of the Hells Canyon Complex. Generally, temperatures upstream of the Hells Canyon Complex are warmer during the spring and summer months relative to the pre-development era (pre-1860). This thermal inertia influences the magnitude and duration of the thermal shift downstream of Hells Canyon Dam that was created by the operation of the HCC.

2. The presence of the HCC has also created warmer over-winter base temperatures in the area below Hells Canyon Dam relative to the pre-development era because of the large volume of 4ºC water stored in Brownlee Reservoir over the winter months.

3. The primary effect of this altered thermal regime to the various life stages are as follows:

   a. *Adult migration* – There has been no apparent shift in adult migration timing. Adult fall Chinook salmon experience a similar period of exposure to temperatures elevated above 20 ºC between mid-August and mid-September as they did pre-HCC, but experience a lower maximum temperature than occurred historically. This is based on water temperatures present at Central Ferry in the early to mid-1950's, prior to construction of the HCC or the lower Snake River reservoirs.

b. *Pre-spawn mortality* – Some level of pre-spawning mortality among anadromous salmonids is common. There is evidence that adult salmon in hatchery holding environments exposed to prolonged periods of water temperatures > 19 ºC could be subject to significant pre-spawn mortality. In hatchery holding situations, the mortality is usually associated with increased susceptibility to disease. However, fish-to-redd ratios documented in the Snake River do not suggest excessive pre-spawn mortality of fall Chinook salmon. It may be that the non-confined environment of a large river under a naturally declining thermal regime and the availability of cooler refuge makes fish less susceptible to disease and mortality. In addition, the HCC has cooled late summer outflows relative to levels associated with the inflow temperature and the operations of Dworshak Reservoir substantially cool areas associated with Lower Granite Reservoir and create thermal refugia during the early pre-spawn environment such that conditions prevalent today are better than conditions prior to the HCC.

c. *Gamete viability* – A through review of the literature demonstrates that studies often cited to suggest reduced gamete viability as a result of prolonged exposure to warmer temperatures should not be cited as supporting literature. The studies typically were not designed to address the question. One study that could be cited as supporting evidence (Jensen et al. 2006) did not hold adult Chinook salmon in a declining thermal regime typical of a riverine environment, but rather exemplified relatively long-term (40-days) exposure to elevated water temperatures. In addition, the control group held fish in a constant thermal environment of between 8 and 9 ºC, which cannot be compared to a declining thermal regime under more normative environments. Based on the available information, it is difficult to conclude that the HCC has had an adverse effect on development of gametes in returning adult fall Chinook salmon.

d. *Disease susceptibility* – Similar to the findings discussed under pre-spawn mortality, adults held in confined hatchery environments under prolonged periods of elevated temperature appear to have a greater susceptibility to disease or fungal infections. How this pertains to free-ranging adults is uncertain. However as discussed above, fish-to-redd ratios do not suggest a high level of pre-spawn mortality below Hells Canyon Dam.

e. *Spawn timing* – There is no evidence that spawn timing has been greatly altered in the Snake River when comparing pre-HCC spawn distribution to that of the present-day Hells Canyon spawn distribution.

f. *Incubation Survival* – Experiments based on constant and declining thermal regimes differ markedly in their results with respect to both ultimate survival and size of fry at emergence. To assess the thermal requirements of incubating eggs in a natural declining thermal regime, Olson and Foster (1955), Olson et al. (1970) and Geist et al. (2006) are the most applicable findings to conditions experienced by Snake River fall Chinook salmon. These studies suggest that eggs spawned at initial temperatures of between 16 ºC to16.5 ºC do not experience different levels of mortality from those eggs spawned at temperatures as low as 13 ºC. At temperatures above 16.5 ºC, mortality of incubating embryos substantially increases. The thermal shift that occurs below Hells Canyon Dam delays cooling of water temperature in the fall and significantly advances the emergence timing of juvenile fall Chinook salmon closer to what occurred historically in the primary production areas upstream of the Hells Canyon Complex. The HCC is now more suitable for the expression of an Age-0 fall Chinook salmon life history than it was before construction of the HCC. The elevated winter base temperatures also contribute to the advanced emergence timing relative to pre-HCC.

g. *Effects of intragravel water temperature* – In Hells Canyon, there is a strong connection between the water column and the redd environment that allows for similar thermal conditions between the two environments. Therefore, the water column conditions provide good metrics for describing the thermal conditions of incubating embryos in Hells Canyon.

h. *Emergence / Outmigration Timing* - Fall Chinook salmon emerge earlier today in Hells Canyon than they did historically in Hells Canyon because of the warmer incubation conditions present today as a result of the HCC. Historically, Hells Canyon was a very cold environment and may not have been conducive for production of an Age-0 migrating fall Chinook salmon. The construction of the HCC altered the thermal regime such that emergence timing is now closer to what occurred historically in the production areas upstream of the HCC. During the 1990's, there was evidence that juvenile outmigration was delayed based on their arrival timing at Lower Granite Dam. Migration through the large slack water environment of Lower Granite Reservoir is more likely to explain the delay observed during that time. Recently, there is evidence of an earlier shift in the outmigration timing at Lower Granite. Fall Chinook salmon appear to be migrating earlier and at a smaller size than observed in the 1990's. Why this trend is occurring is uncertain, but may relate in some way to density in the rearing areas as adult returns and natural production has continued to increase.

1. Introduction

The purpose of this white paper is to consolidate information relative to water temperature and fall Chinook salmon below Hells Canyon Dam. The paper reviews applicable water quality criteria for the Snake River for fall Chinook salmon. It reviews the anthropogenic influences in the Snake River. Significant anthropogenic influences on water temperature have occurred in the Snake River basin both upstream of Hells Canyon Dam and as a result of the Hells Canyon Complex. Generally, upstream of the Hells Canyon Complex is warmer during the spring and summer months relative to the pre-development era (pre-1860). This thermal inertia influences the magnitude and duration of the thermal shift downstream of Hells Canyon Dam that was created by the operation of the HCC. This paper discusses what the effect of those changes are to fall Chinook salmon life-stages dependent upon the habitats below Hells Canyon Dam today.

2. Review of Temperature Criteria for the Snake River

For purposes of this report, the temperature criteria assessment for the Snake River was limited to the stretch of the river forming the border between Idaho and Oregon (RM 409 – 169). Application of temperature standards in Oregon and Idaho is similar. Both states have five types of temperature standards: 1) biologically-based criteria that ensure thermally optimal conditions; 2) natural conditions (as determined by the states), which supersede biologically-based criteria; 3) air temperature exclusion criteria that allow for exceedence of numeric and natural conditions; 4) human use allowance, which allow insignificant additions of heat due to anthropogenic sources; and 5) site-specific criteria, requiring water-body specific rulemaking that is based on the unique characteristics of the watershed (IDAPA 58.01.02. n.d., OAR 340-041 n.d.). Temperature criteria are applicable to specified locales and times depending on the species and activities that are present. Additionally, Oregon standards require that the seasonal thermal pattern in the Snake River must reflect the natural seasonal thermal pattern (OAR 340-041-0028(4)(d)). The purpose of temperature criteria is to protect designated temperature-sensitive beneficial uses, including specific salmonid life cycle stages, when and where those uses occur.

While both Oregon and Idaho similarly apply temperature standards, the biologically-based criteria differ. The SR-HC TMDL established the most conservative criteria as the targets for attainment of water quality standards and protection of designated beneficial uses (IDEQ and ODEQ 2004). Both Oregon and Idaho have since revised their water quality standards, including the temperature standards. IPC presented these changes in its revised § 401 certification application, where appropriate, and attempted to identify the most conservative criteria to be consistent with the approach used in the SR-HC TMDL.

2.1 Aquatic Life and Salmonid Rearing

The aquatic life beneficial use classifications are for waters that are suitable or intended to be made suitable for protection and maintenance of viable communities of aquatic organisms of significant aquatic species (IDEQ and ODEQ 2004). Resident and anadromous salmonids exist in the HCC and Snake River, and the applicable biologically-based criteria are dependent on their distribution. Resident salmonids, particularly redband trout, exist upstream of Hells Canyon Dam. Anadromous fall Chinook salmon and steelhead inhabit the Snake River downstream of Hells Canyon Dam. Significant viable populations of cool and warm water aquatic species exist in the HCC reservoirs. These include predominantly smallmouth bass (*Micropterus dolomieui*), black crappie (*Pomoxis nigromaculatus*), and white crappie (*P. annularis*) (Richter and Chandler 2003).

The SR-HC TMDL evaluation of Oregon and Idaho water quality standards, as first published in 2003, identified as most conservative the then existing Oregon numeric temperature criterion for salmonid rearing of a seven-day average maximum temperature of 17.8 °C (IDEQ and ODEQ 2004). Therefore, the SR-HC TMDL temperature target was established at this criterion to be applied year round to the HCC reservoirs and outflows with June to September as the critical time period.[1] Oregon has since revised its water quality standards, including temperature standards. Oregon currently has two temperature criteria applicable to waters of the HCC and Snake River.

- The seven-day average maximum temperature of a stream identified as having Lahontan cutthroat trout or redband trout use may not exceed 20.0 °C (OAR 340-041-0028(4)(e)). This criterion is applicable to the HCC reservoirs and Snake River from RM 247.5 to RM 409.
- The seven-day average maximum temperature of a stream identified as having a migration corridor use for salmon and steelhead may not exceed 20.0 °C (OAR 340-041-0028(4)(d)). This criterion is applicable to the Snake River from RM 169 to RM 247.5. In addition, there must be sufficiently distributed coldwater refugia to allow salmon and steelhead migration without significant adverse effects from higher water temperatures elsewhere in the water body. Finally, the seasonal thermal pattern in Columbia and Snake Rivers must reflect the natural seasonal thermal pattern.

Idaho temperature criteria for the protection of cold water aquatic life are a daily maximum not to exceed 22 ºC with a maximum daily average of no greater than 19 ºC (IDAPA 58.01.02.250.02.b.). IPC believes Oregon's temperature criteria are still more conservative than Idaho's and its revised § 401 certification application evaluated

[1] There are two exceptions. The numeric criterion does not apply when the temperature in excess is naturally occurring or when the daily maximum air temperature exceeds the 90th percentile of the seven-day average daily maximum air temperature calculated over a ten-year period.

conditions relative to standards using Oregon's seven-day average maximum criteria of 20 °C applied year round in the HCC reservoirs and outflows.

2.2 Salmonid Spawning

Oregon and Idaho have criteria to protect spawning salmonids in areas and during times the species are present. The SR-HC TMDL stated that water quality standards for salmonid spawning would apply only to that portion of the Snake River below Hells Canyon Dam (RM 247 to 188) from October 23 through April 15 for fall Chinook salmon and November 1 through March 30 for mountain whitefish (IDEQ and ODEQ 2004). The SR-HC TMDL used Idaho's criterion, which is a maximum weekly maximum temperature of 13.0 °C (IDAPA 58.01.02.286.).

Oregon's salmon and steelhead spawning temperature criterion is a seven-day average maximum temperature not to exceed 13.0 °C (OAR 340-041-0028(4)(a)). This criterion is applicable to the Snake River from RM 188 to RM 247.5 from October 23 through April 15 and from RM 169 to RM 188 from November 1 through May 15. In addition, Oregon has revised the human use allowance standard (OAR 340-041-0028(12)(b)) to include a cumulative increase from anthropogenic sources of no more than 0.3 °C above the applicable criteria. Idaho criteria apply in the Snake River downstream of Hells Canyon Dam to the confluence with the Salmon River; RM 188-247.5. Specifically, a maximum weekly maximum temperature of 13 °C applies from October 23 through April 15 (IDAPA 58.01.02.286).

Consistent with the SR-HC TMDL, IPC attempted to evaluate conditions relative to the most conservative standard in either Oregon or Idaho. While the Idaho calculation of a maximum weekly maximum temperature (IDAPA 58.01.02.010.55) is different than the Oregon seven-day average maximum temperature (OAR 340-041-0002(54)), IPC believes the objectives of both criteria, not to exceed 13 ºC on the most critical consecutive seven-day period, are similar. Therefore, IPC evaluated data, in relation to salmonid spawning, against a seven-day average maximum not to exceed 13 ºC.

The IDEQ and ODEQ have interpreted the seven-day average maximum temperature to be the mean of daily maximum temperatures measured over a consecutive seven day period ending on the day of calculation. This interpretation is part of an Idaho proposed rule change (IDEQ 2006) and an Internal Management Directive being drafted by Oregon (ODEQ 2006). Both follow EPA's recommended guidance (USEPA 2003).The salmonid spawning temperature criterion below the HCC starts on October 23. Applying the criterion in accordance with the IDEQ and ODEQ interpretation, the seven-day average maximum temperature is first calculated on October 29.

3. Influence of Anthropogenic activities upstream of HCC

3.1 Estimated Historic Temperature

Water quality in Hells Canyon reservoirs and releases from the Hells Canyon Complex is a function inflowing water quality as well as in-reservoir processes. Instantaneous temperatures greater than the 20 ºC criterion for cold water biota have been documented to likely occur in all years in both the HCC reservoirs and releases (IPC 2007). Likewise, temperatures greater than the seven-day average maximum temperature criterion of 13 ºC for salmonid spawning occur in most years. The elevated temperatures that exceed the criterion occur during the first few weeks of the fall Chinook salmon spawning season.

In addition to numeric criteria, Oregon has a narrative temperature standard applicable to the Snake and Columbia Rivers. Specifically, the standard requires that the waters reflect the natural seasonal thermal pattern (OAR 340-041-0028(4)(d)). While this standard is different than the natural condition standard (IDAPA 58.01.02.200.09, OAR 340-041-0028(8)), the SR-HC TMDL stated it is difficult to determine what natural temperature conditions are for such a highly regulated system or precisely how altered current conditions are from natural conditions (IDEQ and ODEQ 2004).

The SR-HC TMDL presented a site potential analysis in an attempt to more accurately assess the influence of the HCC on water temperatures downstream. Site potential was defined as the temperature that is predicted to have occurred with direct sources of heat (predominately natural atmospheric inputs) to the mainstem Snake River and without the influence of the HCC, but assuming the current altered hydrologic regime, climate, and tributary inputs (IDEQ and ODEQ 2004). Thus, the SR-HC TMDL used inflow temperatures measured at Brownlee Reservoir as an estimate of site potential in the Snake River downstream of the HCC. This was done despite the fact that the SR-HC TMDL determined that elevated temperatures in the Snake River are primarily due to natural sources and anthropogenic sources, such as upstream and tributary impoundments, water withdrawals, channel straightening and diking, and removal of streamside vegetation that cannot be precisely quantified, and which were not adequately considered in the SR-HC TMDL analysis of site potential. IDEQ and ODEQ acknowledged at the time that this estimate should not be interpreted as natural conditions.

IPC concurred that natural condition temperatures for the Snake River prior to Euro-American settlement cannot be precisely determined. However, during the SR-HC TMDL public comment period, IPC asserted that the SR-HC TMDL temperature analysis improperly ignored upstream anthropogenic effects on water temperature (IPC 2002). In its revised § 401 certification application, IPC presented an alternate analysis to estimate site potential of the Snake River. IPC developed estimated historic (EHist) temperature to illustrate that, while quantifying all upstream anthropogenic effects on temperature may not be possible, estimating additional anthropogenic effects beyond what were captured in the SR-HC TMDL is possible. The EHist temperature analysis does not capture all upstream anthropogenic effects, and therefore, likely attributes more responsibility to the HCC than would exist if the "true" natural conditions were realized.

3.1.1 Estimated Historic Temperature Assumptions

Large-scale anthropogenic development in the Snake River watershed began in the late 1800s. Placer mining was the first to appear (Chandler 2001). As mining activities increased, so did industries that could serve the growing population. Quickly, the watershed was developed for timber harvest and agricultural and livestock production. Some of the most profound hydrologic changes began with the development of irrigation systems. Irrigation systems in the upper Snake River valley served more than 500,000 acres of croplands by 1900 (USBOR 2006). More detail on the anthropogenic development of the Snake River watershed is available in Chandler and Chapman 2001, and Chandler et al. 2001. IPC's EHist temperature analysis was developed to account for hydrologic and temperature changes in the Snake River due to anthropogenic development. Specifically, the EHist temperature model accounted for water diversion and storage upstream of the HCC; an estimate of unaltered water temperatures in a large river system affected by similar landscape and climatological influences; and natural springs in the Middle Snake River, collectively known as Thousand Springs.

IPC assumed a U.S. Army Corps of Engineers (COE) estimate of unregulated flow upstream of the HCC represented natural hydrologic conditions prior to large-scale anthropogenic development in the Snake River watershed. The COE estimate accounted for storage and diversions (USCOE 2005). Essentially, the current computed local gauge flow below storage facilities was adjusted based on operations or changes in storage. This was termed the adjusted local gauge flow. From the adjusted local gauge flow, diversion flows obtained from the Idaho Department of Water Resources were added. This iterative computation was carried throughout the Snake River watershed and resulted in an estimate of unregulated flow for the Snake River at Weiser, Idaho. The COE unregulated flow estimate was calculated based on daily average flow and thus incorporated seasonal variability in flow.

To use the COE estimate of unregulated flow in the EHist temperature analysis, assumptions of temperature conditions before widespread anthropogenic development were needed because measured water temperature data do not exist. Therefore, a surrogate was used. IPC identified the Salmon River as appropriate for use in the EHist temperature analysis. The Salmon River watershed is situated immediately north of the Snake River inflow to the HCC. Unlike the Snake River, flow from the Salmon River is effectively unregulated. The SR-HC TMDL stated the total storage capacity in the watershed is less than 0.1% of the Salmon River average annual runoff (IDEQ and ODEQ 2004). Large portions of the watershed are in wilderness or roadless areas, and the watershed is very sparsely populated. These factors combine to make the Salmon River, while not pristine, the most natural river in the region of comparable size to the Snake River. In addition, the Salmon River has similar landscape and climatological influences. IPC assumed Salmon River temperatures measured near the confluence with the Snake River (960 ft msl) were representative of temperatures expected in the Snake River inflow to Brownlee Reservoir (2077 ft msl) without spring discharges prior to large-scale anthropogenic development. IPC believes this is a conservative assumption as the Salmon River confluence with the Snake River is located at a lower elevation than Brownlee Reservoir. IPC used daily average temperature data.[2] These data incorporated variability as a result of climatological influences.

The temperature effects of spring discharges on Snake River temperature are included in the EHist temperature analysis. Snake River spring discharge areas occur primarily along two reaches: in the upper Snake River near American Falls Reservoir (RM 675) and in the middle Snake River in an area known as Thousand Springs (RM 585). The Thousand Springs section of the Snake River is a dispersed area covering about 35 river miles. Cumulative discharge has changed over the years with extensive water development in the Snake River watershed. Estimated Thousand Springs cumulative discharge was 4,800 cfs in 1915 increasing to 6,800 cfs in 1955 (IWRRI 2006). IPC assumed the 1915 estimated cumulative discharge of 4,800 cfs best represented the spring discharge prior to large-scale anthropogenic development in the watershed. This estimate is applied as a constant average daily flow and does not account for seasonal variability in spring discharge. The SR-HC TMDL reported the median temperature of ground water inflows to the Snake River were 14.5 ºC (IDEQ and ODEQ 2004). This is corroborated by a mean water temperature of 14.7 ºC reported by Brink and Wilkison (2001) for a predominately spring fed reach of the Malad River, an area in close proximity to Thousand Springs. IPC assumed the Thousand Springs discharge was represented at 14.5 ºC. Climatological influences affect water temperature as water is transported through a watershed. That is, water temperatures tend to reach equilibrium with the climate (e.g., solar radiation, atmospheric air temperatures, wind, humidity). This should not be a factor in applying Salmon River temperatures to the Snake River unregulated flow portion of the inflow to Brownlee Reservoir, however, it may affect spring discharge temperatures applied to the EHist temperature model. IPC did not assume longitudinal warming or cooling of Thousand Springs discharges. Temperature effects from spring water discharged near American Falls Reservoir (RM 675) were not specifically accounted for in the EHist temperature analysis and indirectly were accounted for in the unregulated flow. IWRRI (2006) estimated 2600 cfs is currently discharged to the Snake River in the reach from American Falls Reservoir to Blackfoot, Idaho.

3.1.2 Estimated Historic Temperature Methodology

Data for the EHist temperature model are presented in Exhibit 6.1-1 of the IPC 401 certification application (IPC 2007). Six years were modeled: 1992, 1994, 1995, 1997, 1999, and 2002. These years represented a range in hydrologic conditions (Table 1).

[2] Temperature data were collected using a Hobo® thermistor following standard operating procedures.

Table 1. Snake River average annual flow in cubic feet per second measured at Weiser, Idaho (U.S. Geological Survey gauge 13269000) from 1911 to 2005 and water year categories estimated on pentile (Table 6.1-4 in IPC 2007).

Water Year Category	Average Annual Flow	Model Year (Average Annual Flow)
Low	< 12,800	1992 (8,400), 1994 (10,800), 2002 (11,000)
Medium-low	12,800—15,400	–
Medium	15,400—18,500	1995 (17,500)
Medium-high	18,500—22,900	1999 (22,900)
High	>22,900	1997 (31,300)

Data for any particular year may not be complete. When data were incomplete, IPC substituted data from a similar water year or a lower water year. IPC believes this is a conservative assumption as conditions, flow and temperature, would be more critical in a lower water year. For example, if Salmon River daily average temperature was unavailable for 1994, Salmon River daily average temperature from another low-water year, like 1992, was used to develop a complete data record. The logic sequence used to develop complete data records for the EHist temperature analysis is described in Table 2. The COE began estimating unregulated flow on October 1, 1992. Therefore, 1992 COE unregulated Snake River flow prior to that date is represented by daily average COE unregulated flow from 1994.

Table 2. Salmon River daily average temperature data record development for estimated historic Snake River temperature analysis by model year. Primary choice indicates the year first chosen if data were missing. Secondary choice indicates the next year chosen to complete the data record. NN indicates data substitution not needed (Table 6.1-8 in IPC 2007).

Model Year	Primary Choice	Secondary Choice
1992	NN	
1994	1992	
1995	2000	
1997	1998	1999
1999	1998	
2002	NN	

The EHist temperature model accounts for water diversion and storage upstream of the HCC; an estimate of unaltered water temperatures in a large river system affected by similar landscape and climatological influences; and natural springs in the middle Snake River, collectively known as Thousand Springs. The model (Equation 1) is simply a flow-weighting of Salmon River and Thousand Springs temperatures. Daily average

EHist temperatures for the six modeled years are presented in Exhibit 6.1-2 of the IPC 401 certification application (IPC 2007).

(Equation 1)

$$\frac{(Spring_{Q} \times Spring_{Temp}) + ((Snake\ River\ Unreg_{Q} - Spring_{Q}) \times Salmon\ River_{Temp})}{Snake\ River\ Unreg_{Q}}$$

Where:

$Spring_{Q}$	= historic cumulative flow from Thousand Springs
$Spring_{Temp}$	= median temperature of Thousand Spring discharge
Snake River $Unreg_{Q}$	= Snake River unregulated flow upstream of the HCC
Salmon $River_{Temp}$	= measured Salmon River water temperature

3.1.3 Estimated Historic Temperature Analysis

Current measured inflow temperatures to the HCC were generally warmer than EHist temperatures, nearly yearlong (Figure 1). This was most obvious starting in the spring and persisting through the summer. This period corresponded with the time of year water is being actively managed in the watershed for agricultural uses. This finding is consistent with the conclusion in USEPA (1974) that reported flow depletion due to storage and diversion, and the return of irrigation waters warmed on fields, has resulted in increased warming of Snake River water temperatures.

IPC used EHist temperatures to evaluate current conditions outflow from the HCC relative to the narrative standard that requires the Snake River reflect the natural seasonal thermal pattern. This evaluation indicated that current conditions below the HCC approximate spring and summer EHist temperatures in the low- and medium-water years (Figure 2). This was in contrast to current spring and summer inflow temperatures, which were consistently much warmer than EHist temperatures (Figure 1). In high-water years, like 1997, outflow temperatures from the HCC did not approximate spring EHist temperatures (Figure 2). COE mandated drawdowns of Brownlee Reservoir for flood control, and the resulting shorter residence time in these years, caused spring inflow waters to be more quickly moved through the HCC resulting in outflow temperatures that were very similar to inflow. In addition, current outflow temperatures from the HCC during the falling thermal regime were warmer than the EHist temperatures in all years. This may partly be the result of the HCC absorbing the elevated spring and summer temperatures and distributing the unnatural thermal load through to the fall and early winter. The conclusion was that in the spring and summer of low- and medium-water years the HCC tended to return the Snake River thermal pattern closer to conditions representative of EHist temperatures than the current inflow temperatures. Thus, the effect of the HCC was to moderate the noncompliant inflow thermal regime closer to the natural seasonal thermal pattern most of the year.

The EHist temperature model illustrates that the current HCC inflowing temperatures are unnaturally high because of upstream watershed activities and do not adequately represent site potential as used in the SR-HC TMDL (Figure 1). These elevated temperatures affect the ability of the HCC outflow waters to meet numeric criteria. IPC used CE-QUAL-W2 models and EHist temperature inflow to Brownlee Reservoir to evaluate the effect of the HCC on outflow temperatures. Only the baseline thermal regime was modified. Current flow and operations were not changed. When EHist temperatures were assigned to water flowing into the HCC, outflow temperatures moved toward compliance with the numeric criteria (Figures 3 and 4).

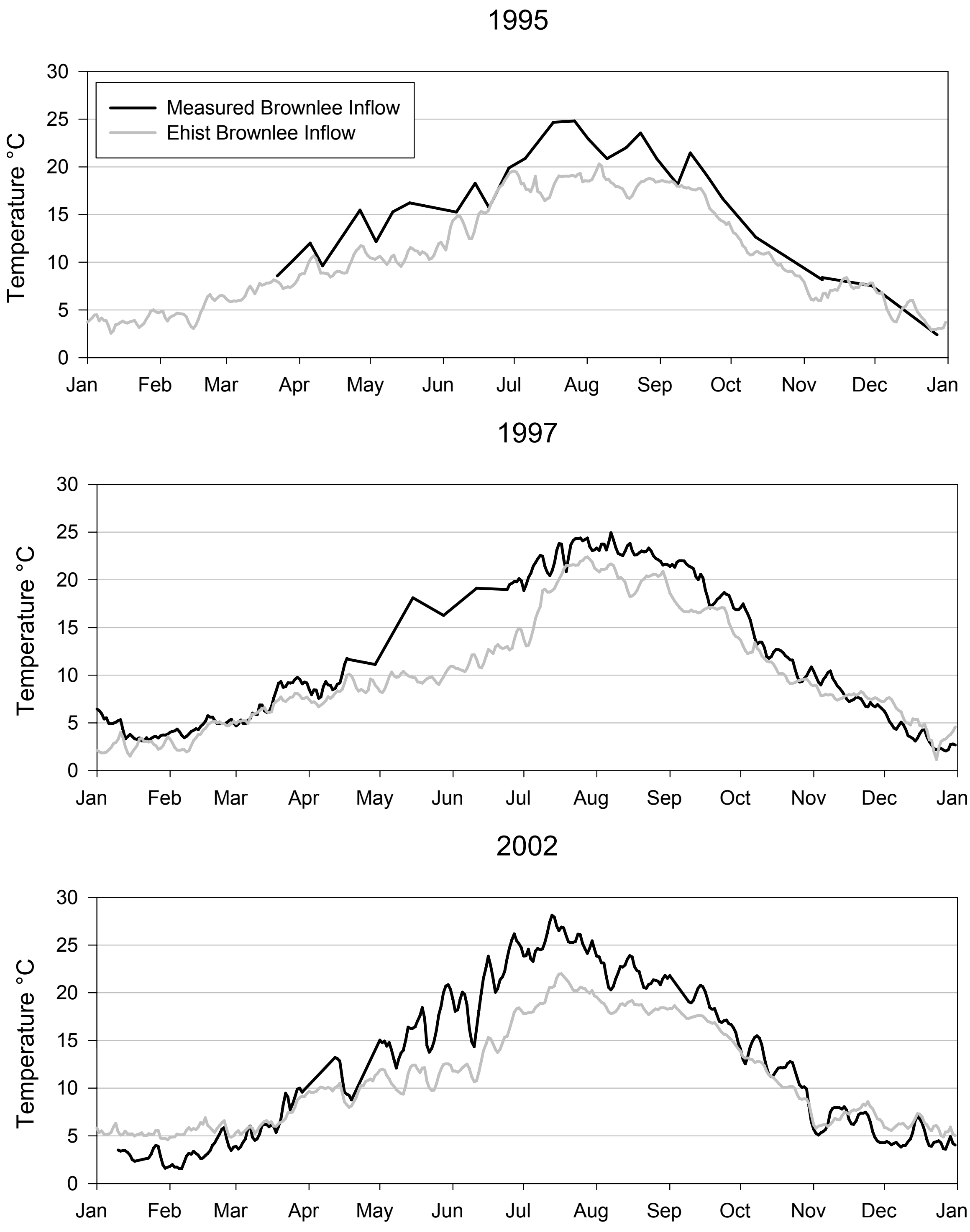

Figure 1. Measured and estimated historic (EHist) temperatures in degree Centigrade (°C) in the Snake River inflow to Brownlee Reservoir for medium (1995), high (1997) and low (2002) water years (Figure 6.1-3 in IPC 2007).

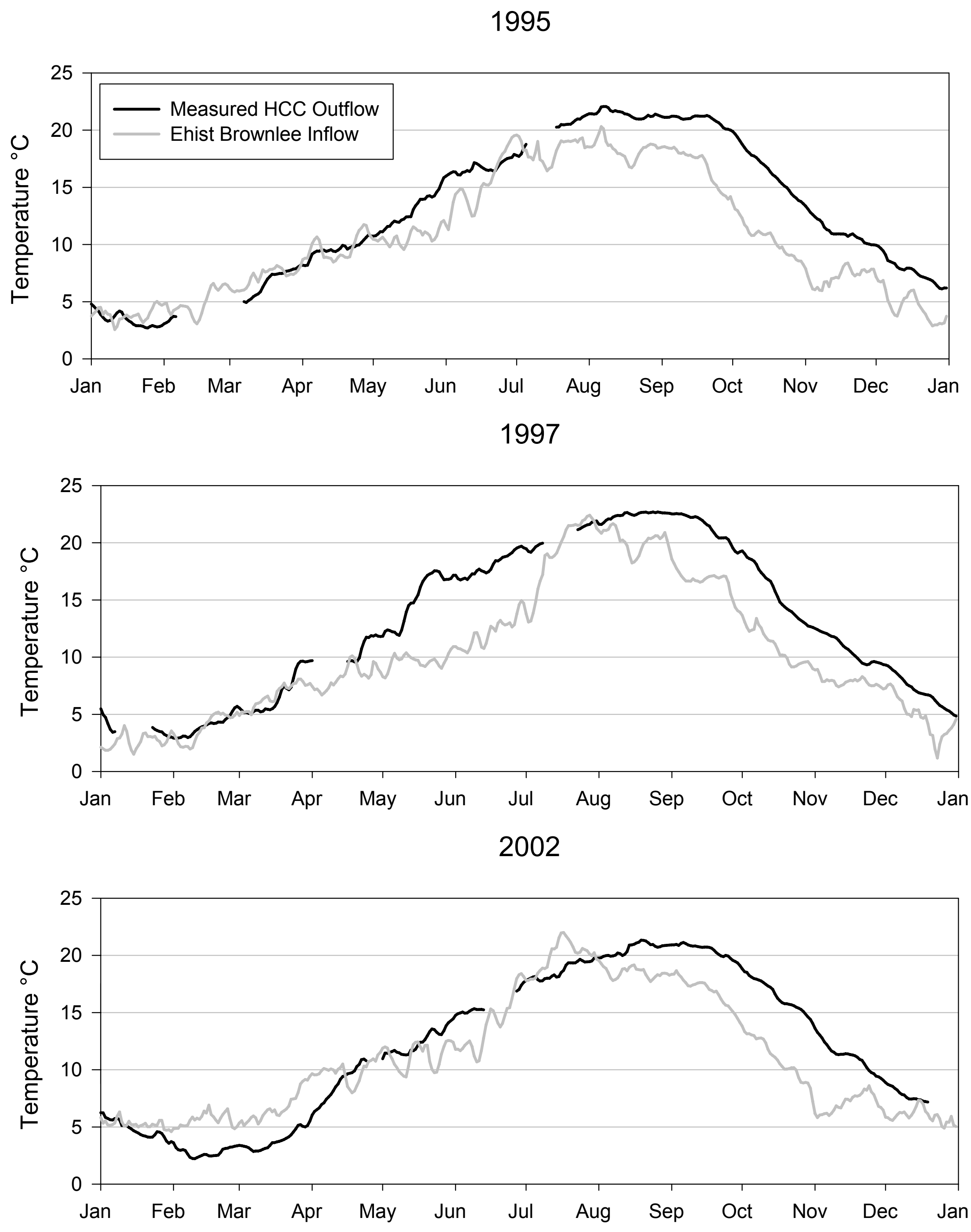

Figure 2. Measured Hells Canyon Complex (HCC) outflow temperatures in degree Centigrade (°C) and estimated historic (EHist) inflow temperatures in the Snake River for medium (1995), high (1997) and low (2002) water years (Figure 6.1-4 from IPC 2007).

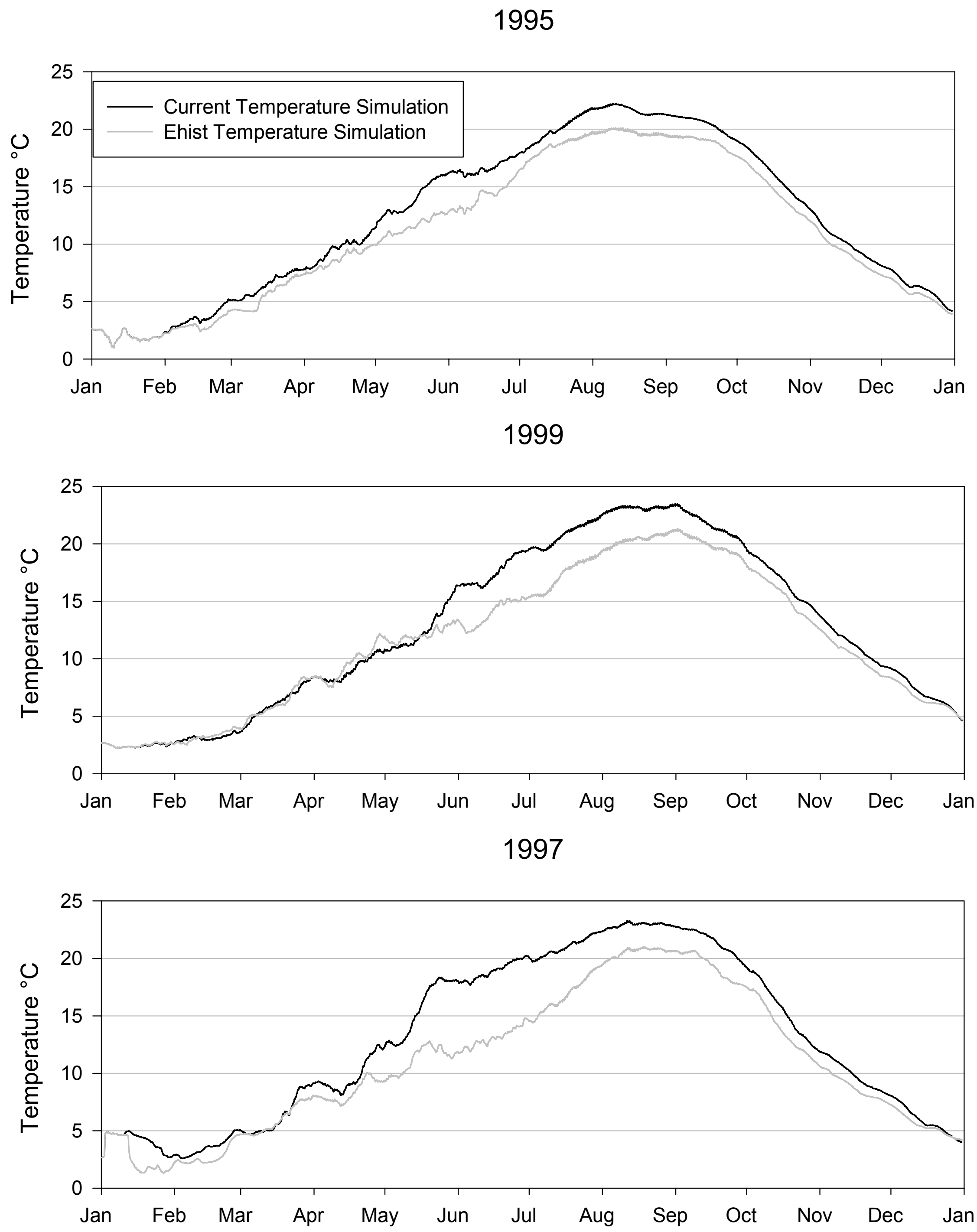

Figure 3. Modeled Hells Canyon Complex outflow temperatures in degree Centigrade (°C) using current (baseline) and estimated historic (EHist) temperatures inflow to Brownlee Reservoir for medium (1995), medium–high (1999) and high (1997) water years (Figure 6.1-5 from IPC 2007).

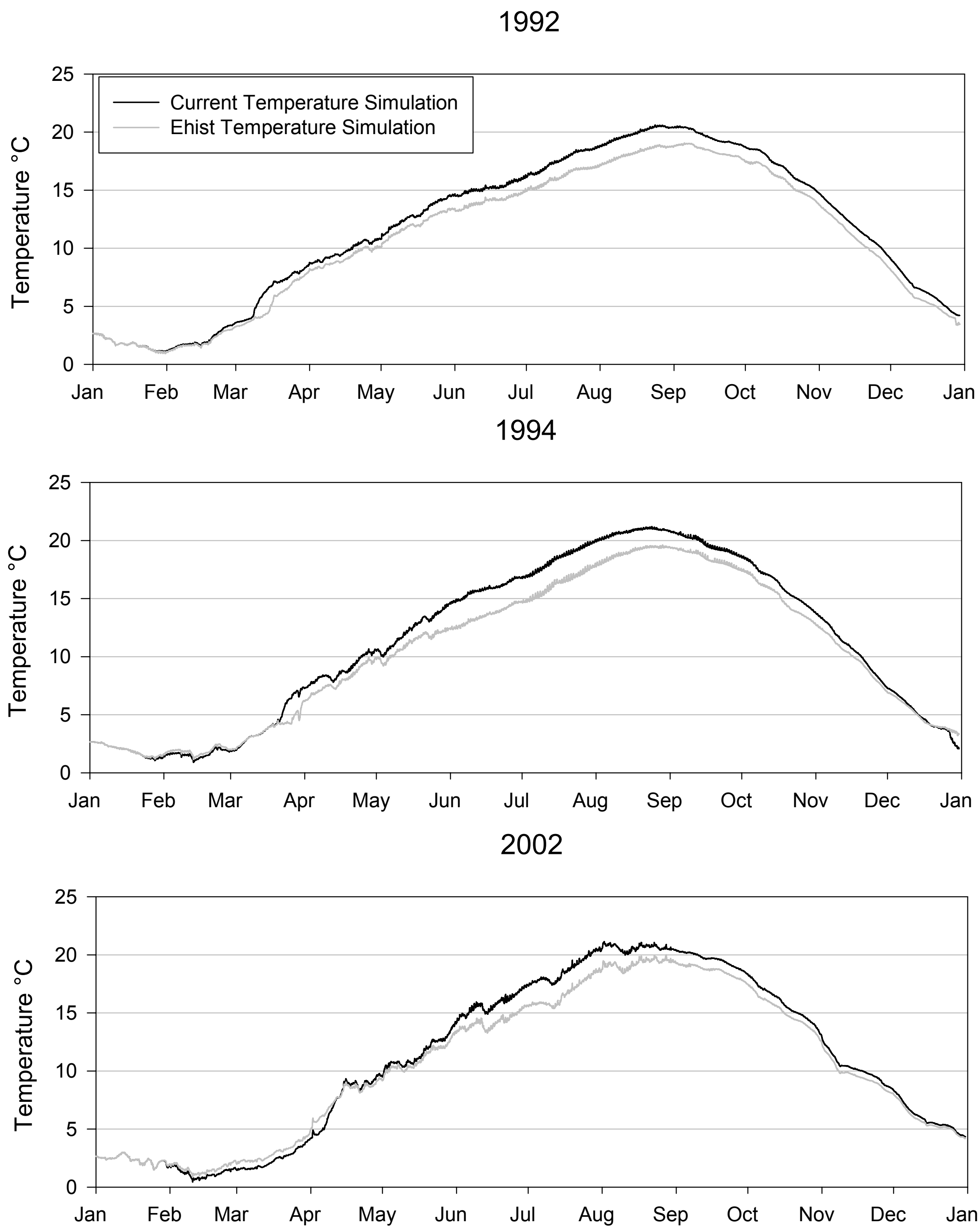

Figure 4. Modeled Hells Canyon Complex outflow temperatures in degree Centigrade (°C) using current (baseline) and estimated historic (EHist) temperatures inflow to Brownlee Reservoir for low water years (1992, 1994 and 2002)(Figure 6.1-6 from IPC 2007).

As discussed above, and demonstrated by EHist, the pre-historic thermal regime below the Hells Canyon Complex substantially differed from the present-day thermal regime and was likely strongly influenced by the inflow of several large tributaries in the area between Swan Falls Dam and the upper portion of what is now Brownlee Reservoir. In this reach of river, the Boise, Payette, Owyhee, Weiser, Malheur and Burnt rivers all enter into the Snake River. This would strongly influence the spring moderated regime upstream of Swan Falls Dam. In addition, the orientation of the high canyon walls in this reach likely limited the solar input during winter months, which contributed to Hells Canyon being a relatively cold over-winter environment, even colder than suggested by EHist, which would represent the Snake River at the point of inflow into Brownlee Reservoir. This colder thermal regime likely affected the production potential of a fall Chinook salmon life history where juveniles initiate seaward migration as an Age-0 fish.

As discussed later (section 4.5), there is little evidence that spawn timing has changed appreciably today as compared to spawn timing prior to the construction of the Hells Canyon Complex below Swan Falls Dam. Spawning was initiated in early October and extended over a relatively prolonged period through early December, with peak spawning occurring around the first week of November (Zimmer 1950). This is very similar to what has been observed today in the spawning area below Hells Canyon Dam. This initiation of spawn timing does not seem strongly tied to a specific water temperatures with the exception that spawning generally takes place when temperature begin to drop below 16ºC and that temperatures are on a declining limb associated with fall cooling (Healey 1991). In fact, spawning has been observed to initiate in water temperatures warmer than 16 ºC. If it is accepted that spawn timing has not appreciably changed, then the influence of different thermal regimes and their effect on emergence timing and outmigration timing of juvenile fall Chinook salmon becomes apparent. IPC hypothesizes that spawn timing of fall Chinook salmon is primarily driven by a declining thermal regime and photoperiod and therefore similar among different rivers and river reaches, and that the effect of different thermal regimes during incubation is manifested in emergence and outmigration timing.

Chandler et al. (2001) compared thermal regimes of different locations in the Snake River relative to emergence timing, including below Bliss Dam (upstream of CJ Strike Reservoir), below Swan Falls Dam (Marsing Reach), downstream of the Weiser River (inflow to Brownlee), Upper Hells Canyon (upstream of Salmon River confluence), Lower Hells Canyon and pre-Hells Canyon Dam (1955-1956; measured at Oxbow, Oregon). For comparative purposes, the Salmon River was also included in the evaluation. In the Bliss Reach, emergence would have been the earliest. Temperatures were relatively stable during the incubation period, and generally did not drop below 7ºC. The latest emergence dates occurred in the Salmon River, with median estimated emergence occurring June 4. Connor (2001) reported estimated emergence timing for the lower Clearwater River as June 17. The Oxbow Reach during the pre-HCC era was also late, with a median emergence date of May 23. Over-winter water temperatures in the Salmon River drop to relatively very low levels. Mean monthly values for December and

January were below 2ºC. The pre-HCC Oxbow reach also reached very low levels and had mean monthly values in January and February below 2ºC. The Salmon River has never been known to support significant numbers of fall Chinook salmon, presumably because of the colder thermal regime. Redds are occasionally observed in the lower Salmon River, but generally represent a very small percentage of the total number of redds observed above Lower Granite Dam (Groves 2001; Groves and Chandler 2001). The similarities between the thermal regime of the Salmon River and the pre-dam Oxbow Reach raise questions as to whether the pre-dam Hells Canyon Reach was capable of meeting its production potential because of thermal limitations.

This comparison demonstrates that emergence timing was correlated with river mile and the altered thermal regime below Hells Canyon Dam shifted emergence present-day earlier than what occurred during the pre-HCC era in the same reach and more in line with the thermal regime upstream of the HCC (Figure 5). The warmer over-winter temperatures likely allow the present-day Hells Canyon Reach to have a higher production potential based on its available present day habitat than what was possible during the pre-HCC era. Similarly, present-day emergence below the Salmon River is also warmer than the pre-HCC era, likely allowing that section of river to reach its production potential based on available habitat. In that regard, the construction of the HCC created thermal conditions that made the 160 km of free-flowing river below Hells Canyon Dam more suitable for fall Chinook salmon spawning than what was evident in the pre-HCC era.

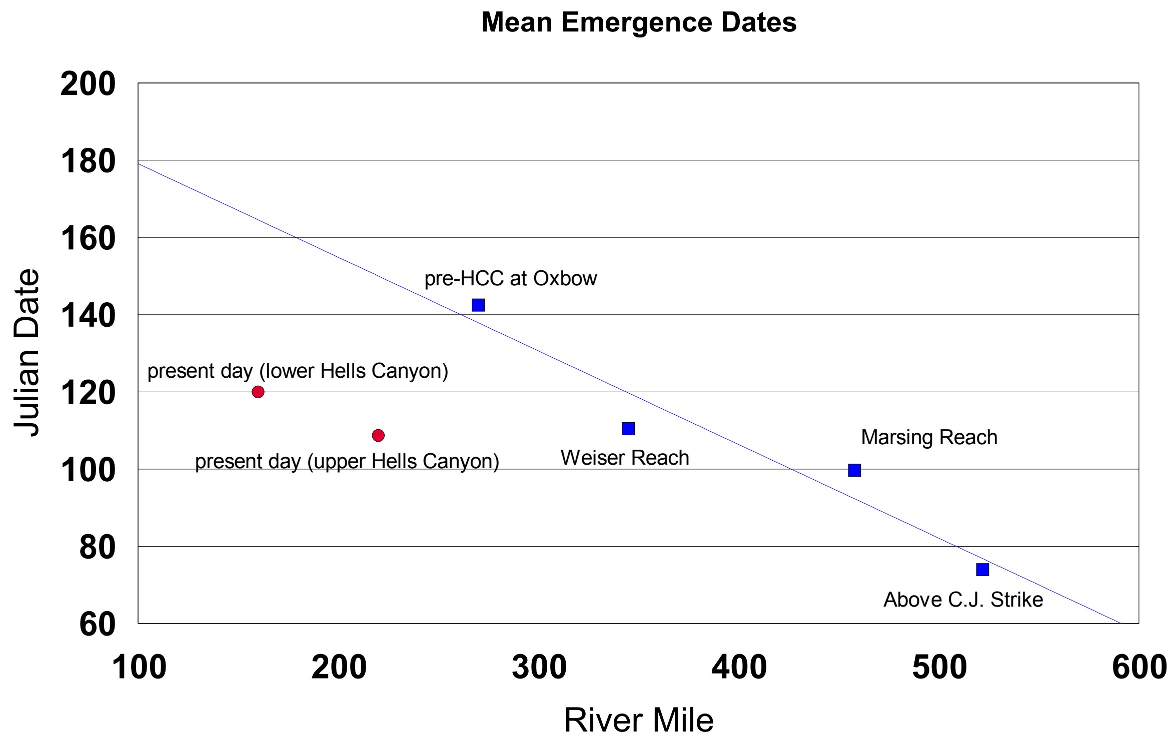

Figure 5. Estimated mean emergence dates of juvenile fall chinook salmon representing the correlation between river mile and emergence day during the pre-Hells Canyon Complex era (blue squares and trend line) and the post Hells Canyon Complex era (red circles).

The effect of Thousand Springs discharge, inflowing near RM 585, on the Snake River thermal regime is evident today with winter temperatures as high as 9 ºC in the reach below Bliss Dam (RM 540). Before the construction of Swan Falls Dam, the middle Snake River in this area was the major producer of Snake River fall Chinook salmon. This comparison demonstrates the influence spring flows had on fall Chinook salmon that allowed them to historically occupy the middle Snake River. Discharges from springs to the Snake River provided critical historic water temperatures that aided fall Chinook salmon embryo development. Spring waters warmed the Snake River during the winter, providing for an earlier fall Chinook salmon emergence than would be expected under a non-spring influenced system and this benefit diminished downstream. This is likely the major reason fall Chinook salmon did not become established in the Salmon River system. Earlier emergence because of warmer winter temperatures was likely an ecological benefit because of the increased distance these fish had to travel to migrate to the ocean. Earlier emergence allowed the ocean-type life history of migrating to the ocean after only a brief rearing period following emergence (the dominant life history) to escape warmer summer temperatures. Early emergence allowed sufficient growth to initiate early migration.

4. Significance of Present-day Thermal Regime to Fall Chinook Salmon

There has been much discussion regarding the potential effects of a thermal shift in the fall prolonging exposure of Snake River fall Chinook salmon to warmer fall temperatures. In this section, we analyzed the different life stages of fall Chinook salmon relative to the thermal shift. Upon review of the information, it is the conclusion of IPC that this thermal shift has had an overall positive effect on Snake River fall Chinook salmon below Hells Canyon Dam because it has allowed fall Chinook salmon to be productive in a reach that prior to construction may not have been able to support significant production. This is significant because historic fall Chinook salmon spawning habitats are either too degraded today to support fall Chinook salmon or are inundated thus leaving the Hells Canyon Reach the only mainstem Snake River habitat suitable to support fall Chinook salmon.

4.1 Adult Migration

Several authors have concluded that elevated water temperatures may adversely affect adult salmon migration. Observations have been reported of adult Chinook salmon upriver migration being stalled or stopped at water temperatures generally greater than 19.0°C (Fish and Hanavan 1948, Sams and Conover 1969, Hallock et al. 1970, Stabler 1981, Alabaster 1988, Bumgarner et al. 1997, Peery et al. 2003). Only three of those references are specific to fall Chinook salmon (Sams and Conover 1969, Hallock et al. 1970, Peery et al. 2003), and only two are specific to or reference Snake River fall Chinook salmon (Sams and Conover 1969, and Peery et al. 2003).

A discussion of adult fall Chinook salmon upstream migration within the Snake River, relative to water temperature, is found within two EPA reports (McCullough 1999, McCullough et al. 2001). Both reports note that historic passage of those fish occurred from late August through November, with a peak in September. Passage data at Ice Harbor Dam (the lowermost dam on the Snake River) shows that from 1964 through 2006 passage of adult fall Chinook salmon has continued to begin in mid-August, peak by about mid-September, and be complete by late-November. The same is presently true for fish passing Lower Granite Dam.

Both EPA reports infer that, due to elevated water temperatures (between 21-25°C) in Lower Granite Reservoir during the period from 13 August to 16 September 1990, a migration blockage of about four weeks occurred, and likely occurs every year. The authors acknowledge that 1990 was one of the warmest years on record, and this event occurred prior to when Dworshak Reservoir discharges began to be used to cool the lower Snake River. If a four week migration blockage had occurred during 1990, then Chinook salmon passage in 1990 should have been near zero during that time period. However, passage data for 1990 shows that 95 adult and 25 jack Chinook salmon passed

Lower Granite during the time period of the warmest water temperature. These fish represented 24% and 13% of each group's total, respectively, of adult and jack fall Chinook salmon counted past Lower Granite Dam during 1990. On average, 33% of adult and 13% of jack fall Chinook salmon tend to pass Lower Granite by 16 September (based on fish passage data from 1974 through 2006). The 24% adult and 13% jack passage during the elevated water temperature period of 1990 does not support the contention that a "migration block" occurred, or occurs in the Snake River.

Sams and Conover (1969) hypothesized that either elevated temperature by itself, or a strong difference in temperature between migration areas might result in either a delay or blockage of migration of Chinook salmon. These authors concluded that water temperatures as high as 22.8°C did not constitute a migration blockage for fall Chinook salmon, nor did their results support that a difference in temperature as large as 5.0°C between two migration areas would cause a delay or blockage to upstream adult migration. They did note that decreased oxygen levels (less than about 4 mg/L) when coupled with elevated water temperature were more likely to cause a migration delay or blockage, than was elevated temperature by itself. Hallock et al. (1970) reported similar conclusions for fall Chinook salmon of the Sacramento-San Joaquin River basin.

In a more recent study, Peery et al. (2003) noted that historic water temperatures at the mouth of the Snake River (prior to any of the lower Snake River dams and the upper river Hells Canyon Complex) were consistently over 20.0°C through mid-September. These authors also reported that water temperatures at the mouth of the Snake River were above 20.0°C for an average of about 71 days historically, but only about 39 days presently. Additionally, since the 1940's mean monthly water temperatures have tended to decrease at the mouth of the Snake River during June, July, and August, remain similar during September, and have slightly increased during October (Peery et al. 2003). However, while those authors report a slight increase for the month of October, it is clear from their data that this is only due to a low sample size, and the inclusion of one very cold year for that monthly period (refer to Figure 6 in their report).

Unfortunately, Peery et al. (2003) were not able to continue their historic/contemporary comparisons to locations further upstream in the Snake River. Limited water temperature data do exist for an area near the present-day location of the Lower Granite Dam (Central Ferry; 1955-1958). Historically, water temperature at Central Ferry tended to increase above 20.0°C by about early July and increase above 21.0°C by about mid-July. Water temperatures tended to reach a maximum of about 25.0°C by about mid-August, remain above 21.0°C until about early September, and finally decrease below 20.0°C by about mid-September. As well, water temperatures at Central Ferry remained above 20.0°C for an average of 71 days; this is similar to what was reported for the mouth of the Snake River by Peery et al. (2003). In comparison, Peery et al. (2003) reported that overall, for the years 1995 through 1998, water temperatures at Lower Granite Dam first reached 20.0°C by about mid July, generally peaked in late July, and tended to finally drop back below 20.0°C by late-September. The average period that water temperatures presently tend to remain above 20.0°C at Lower Granite Dam is 60 days, and the peak temperature averages about 22.0°C (3.0°C cooler than historic temperature maximum).

Based on the above information, it appears that adult fall Chinook salmon presently enter and migrate through the lower Snake River during a time-frame consistent with what is believed to have occurred historically (pre-1964). However, and this is significantly more important, those fish presently appear to experience a similar period of exposure to temperatures elevated above 20.0°C (mid-August through mid-September), but experience a much lower maximum temperature. This is also a conclusion of Peery et al. (2003). This information indicates that fall Chinook salmon do not presently experience a more hostile environment during their upstream migration than they did historically.

Peery et al. (2003) concluded that the passage of low numbers of radio-tagged adults during the warmer period of their study indicated that either a block or a migration delay can occur. Peery et al. (2003) also noted that the 25% passage quartile tended to be completed later in years when water temperatures were warmer. However, it is noteworthy that the adult Chinook salmon used in this study were tagged at Bonneville Dam, and that no data are presented as to the actual timing of the tagging of those fish. Without knowing when the fish were tagged, it is questionable whether the observations of a few radio-tagged fish passing Ice Harbor and Lower Granite dams during mid-July through mid-September were due to water temperature causing a passage block or delay, or more simply because few to no fish were tagged during that period. Water temperatures at Bonneville Dam during their study were consistently ≥20.0°C for the periods from about 29 July – 10 September 1997, and 17 July – 8 September 1998. It is normally not considered prudent to tag adult Chinook salmon when water temperatures are ≥20.0°C (Mendel et al. 1992) due to increased potential for stress-related mortality from handling. Also, while few to none of their radio-tagged subjects were observed passing the two dams during the early period of fall Chinook passage (mid-August through mid-September), it should be noted that only two adult fall Chinook salmon were tagged in 1997, and in both years (1997 and 1998) a large number of un-tagged Chinook salmon were counted (36% and 20% of each years' total run, respectively) during that period at each dam as they passed upstream.

Finally, there is the potential for salmonids to behaviorally regulate their internal body temperatures (Berman 1990, Berman and Quinn 1991). These reports show that adult Chinook salmon are adept at locating and holding in thermal refugia, maintaining their internal body temperatures as much as 2.5°C cooler than ambient water column temperatures. While the presence or amount of potential thermal refugia is unknown throughout the Snake River (either downstream or upstream of Lower Granite Dam), data from 1995 through 2006 show that the water temperature in the tailrace of Lower Granite Dam, during the period 18 August through 30 September, averaged 1.3°C cooler than in the forebay (range 0.4 – 2.1°C cooler). As well, the mean water temperature for that period was 18.4°C in the tailrace and 19.7°C in the forebay. It is reasonable to infer that thermal refugia exist throughout the Snake River, whether in deeper pools, at the mouths of tributaries, or in areas of cooler groundwater upwelling.

In conclusion, there has been no apparent shift in adult migration timing. Adult fall Chinook salmon experience a similar period of exposure to temperatures elevated above

20 ºC between mid-August and mid-September as they did pre-HCC, but experience a lower maximum temperature than occurred historically. This is based on water temperatures present at Central Ferry in the early to mid-1950's, prior to construction of the HCC or the lower Snake River reservoirs.

4.2 Pre-spawn mortality

Some level of pre-spawn mortality is common among salmon populations. Concern is often expressed as to whether excessive pre-spawn mortality occurs in fall Chinook salmon of the Snake River and if it can be linked to elevated water temperature exposure. In McCullough (1999) and McCullough et al. (2001), several references are listed that indicate that temperatures ≤15.0°C in hatchery holding ponds result in the highest survival of adult Chinook salmon prior to spawning. All of the pertinent literature available pertaining to Chinook salmon pre-spawn mortality in relation to water temperature is based on studies of spring or summer Chinook salmon (Coutant 1970, Becker 1973, Lindsay et al. 1989, Berman 1990, Jensen et al. 2005, Jensen et al. 2006). The actual cause of death in most all cases is outbreak of disease associated with long exposure times (as much as seven weeks) at elevated water temperatures (≥19.0°C) and fish being held in stressful conditions and in close contact with each other (e.g. hatchery holding ponds).

Elevated water temperature during adult holding is not necessarily lethal, and may not always result in elevated pre-spawn mortality (Burrows 1960). A major objective of Burrows (1960) was to assist hatchery developers in designing and constructing the most efficient types of adult holding ponds. The author noted that, over a 10-year period at the Entiat hatchery in Washington, even though maximum water temperatures were as high as 22.5°C, and adults were held on average for about three months (which included the warmest seasonal period), there were no statistical differences in survival when compared with cooler years. After examining differences at two different hatcheries (Entiat and Leavenworth), the author noted that the most likely cause of the lower survival rates of spring Chinook salmon at the Leavenworth hatchery was due to a poor flow-through of supply water, not elevated water temperature.

In a study by Berman (1990), spring Chinook salmon adults were maintained at constant control (≈14°C) and test (≈19°C) temperatures for 45 days. At the end of that time period the control fish appeared to be in good shape; however, all but two of the test fish (both males) had perished. Following the loss of the test fish, the control lot was split into a new control and two test groups. The new control group was again maintained at ≈14°C, and the two new test groups were again maintained at ≈19°C. After a period of at least 15 days there were no observed mortalities in either test group. While the actual objective of the study was not to determine how long adult spring Chinook salmon could be held at elevated water temperature without mortality occurring, it does indicate that prolonged holding of adult spring Chinook salmon at water temperatures approximately 19°C can result in significant pre-spawn mortality. It would not be unusual that higher temperatures would produce similar results, and likely take a shorter period of exposure to do so.

Additionally, two recent papers (Jensen et al. 2005, Jensen et al. 2006) provide further evidence that increased pre-spawn mortality can occur if adult Chinook salmon are exposed to elevated water temperatures for a lengthy period of time. In Jensen et al. (2005), adult summer Chinook salmon held in two naturally declining thermal regimes, one heated and one chilled (with respect to ambient river conditions), resulted in overall pre-spawn mortality values of 71% and 58%, respectively. However, what is interesting is that both groups were on-station by 18 August, and by 20 October both groups of fish had experienced equal pre-spawn mortality of 58%. Because the fish in the chilled group had all matured and were spawned by 20 October, there were none to maintain past that date. The authors initially believed that the heated thermal group experienced delayed gamete maturation; however, during a second year of study, that was not the case. During the second year of study (Jensen et al. 2006) all test fish in chilled, ambient, and heated temperature test tanks perished by 1 September, prior to maturation and spawning. However, pre-spawn mortality could be estimated for female fish held in ambient river temperature raceways (46%) and constant cold temperature tanks (8%). The difficulty with this data was that an undetermined, high incidence of predation had occurred to the population of fish maintained in the ambient temperature raceways, which makes the prespawn estimate of 46% inconclusive. In addition, the control fish were held at constant cold (≈9°C) temperatures, which makes application to a natural environment such as a large river difficult. However, it is again reasonable to assume from their data that maintaining adult Chinook salmon at water temperatures consistently ≥19.0°C for approximately 40-45 days will result in elevated pre-spawn mortality. These papers generally confirm the findings reported by Berman (1990).

This information has limited application to the Snake River. Adult fall Chinook salmon generally begin to enter the Snake River by about mid-August. The U.S. Army Corps of Engineers designates 12 August and 18 August as the dates from when salmon passing Ice Harbor and Lower Granite dams, respectively, are deemed fall Chinook salmon. Since 1995, the mean number of days (during the adult fall Chinook salmon passage period) that water temperature is ≥19.0°C in the tailrace of Ice Harbor and Lower Granite Dams is 40 (range 23-55) and 5 (range 0-27), respectively. As an added note, about 57% (mean of passage data for 1964-2005) of the adult fall Chinook run passes Ice Harbor Dam during the first 40 days of passage, when water temperatures in the tailrace can be expected to be ≥19.0°C. Based on this information, it would not be surprising if individual fish remaining in the tailrace of Ice Harbor Dam for as many as 40 days might be subject to pre-spawn mortality. However, a migrating fish remaining in a tailrace for that duration is not likely to occur. The median time for radio-tagged Chinook salmon (combination of spring and fall adult data) to pass Ice Harbor Dam was 16.9 hours in 1997 and 14.4 hours in 1998 (Peery et al. 2003). A shorter amount of time was required to pass the dam during periods when water temperature was the warmest. These authors also reported a median travel time between Ice Harbor and Lower Granite dams of 3.9 days in 1997, and 3.6 days in 1998. These data indicate that while fall Chinook salmon do enter the Snake River when water temperature can be considered lethal over an extended time period, the fish do not typically remain in these warmer conditions for the extended period of time that would suggest the occurrence of high pre-spawn mortality.

As discussed in the previous section on adult migrations, thermal refugia likely exist throughout the Snake River (i.e. confluence of the Clearwater and Snake rivers and near the mouths of several smaller tributaries).

Another indicator of pre-spawn mortality can be the fish to redd ratios determined for fall Chinook salmon upstream of Lower Granite Dam. It has been noted that early fish to redd ratios within the Snake River Basin (previous to 1993) indicated that a very large proportion of the adult population were unaccounted for based on the number of observed redds, and this was often presumed to be because of high levels of pre-spawn mortality. Fish to redd ratios during the period 1986-1992 averaged 24.0, with a very wide range of 7.0-110.3. While these early numbers were cause for concern, it should be understood that only a very limited number of redd surveys, covering a limited portion of potential habitat, were conducted during those years. Another factor in those early years was that there was no attempt to compensate for fallback of adult Chinook salmon (or over-counts) at Lower Granite Dam, or deep-water spawning that was not detectable from the aerial surveys in either the mainstem Snake or Clearwater rivers. Since 1993 a very extensive effort has been expended to count fall Chinook salmon redds in habitats upstream of Lower Granite Dam. Aerial surveys are conducted weekly in the mainstem Snake River, as well as the Clearwater, Grande Ronde, and Imnaha rivers (major tributaries). Additional aerial surveys are conducted within the Salmon River and in the lower portions of a few of the smaller tributaries. Finally, a significant effort is undertaken to enumerate deep-water spawning at many sites in the Snake River using remote underwater video; however, this type of survey method continues to be lacking in the Clearwater River. When all of these data are compiled and analyzed relative to the total number of adult fall Chinook salmon allowed to pass upstream of Lower Granite Dam (with fallback and over-counting at the dam taken into account), the resulting fish to redd ratio has averaged 3.2 (range 2.0-4.2, data from 1993-2006). This comports well with (or better than) estimates of fish to redd ratios for the Hanford Reach of the Columbia River (3.0-16.0), where pre-spawn mortality is not considered to be a problem (Visser et al. 2002), and has never been reported as “excessive”.

It is reasonable to assume that if adult fall Chinook salmon remained for long periods of time where water temperatures remain ≥19.0°C, then significant pre-spawn mortality could likely occur. It is also apparent that water temperature near the mouth of the Snake River can be ≥19.0°C for extended periods of time during the fall Chinook salmon adult migration. If adult fall Chinook salmon were to remain in that area for long periods of time, pre-spawn mortality could be a concern. However, adults do not remain in the vicinity of the mouth of the Snake River (near Ice Harbor Dam) for prolonged periods (especially when it is warm), and they appear to migrate rapidly upstream to cooler reaches (near Lower Granite Dam). Berman (1990) had no trouble maintaining adult spring Chinook salmon at temperatures approximately 19°C for at least 15 days. Additionally, fish to redd ratios for the Snake River upstream of Lower Granite Dam provide further evidence that pre-spawn mortality is not a significant problem.

4.3 Gamete Viability

Another concern relative to pre-spawn exposure to warmer temperatures is a potential reduction in gamete viability which ultimately could lead to a reduced fitness (see reviews in McCullough 1999, and McCullough et al. 2001). These two reports offer a review of available literature of which most refer to species other than Chinook salmon. In fact, it appears that sockeye salmon (Andrew and Geen 1960, Bouck et al. 1975, Gilhousen 1980), coho salmon (Flett et al. 1996), pink salmon (Jensen et al. 2004), rainbow trout (Billard 1985), or brook trout (Hokanson et al. 1973) have been the primary species of study in this area. In these reviews, the Jensen et al. (2004) report on pink salmon is extensively referenced by the authors when making conclusions regarding Chinook salmon embryo viability.

Prior to exploring several references that are specific for Chinook salmon on the topic of reduced gamete success, one aspect of this area of research is noteworthy. Studies concerning this topic vary considerably in their results. Many of the studies cited (although not specific to Chinook salmon) demonstrate that egg and sperm quality can be reduced if "ripe" adults are held for extended periods at consistently high water temperatures. However, there is no evidence presented in these reviews that Chinook salmon adults holding in warmer waters but under a declining thermal regime are subject to reduced gamete viability. Therefore, the applicability of these reviews to not only Chinook salmon but also to natural populations of Chinook salmon experiencing a declining thermal regime that occurs in the natural environment is questionable.

Several reports specific to Chinook salmon that are commonly cited on the topic of gamete viability and temperature include: Hinze et al. (1956), Hinze (1959), Rice (1960), Jewett (1970), Jewett and Menchen (1970), CDWR (1988), Berman and Quinn (1989), Berman (1990), Marine (1992), Jensen et al. (2005). Two of these (CDWR 1988, and Marine 1992) are literature reviews similar to those of McCullough (1999) and McCullough et al. (2001). The following sections will explore in detail these studies and will compare their findings relative to conditions that Snake River fall Chinook salmon experience.

4.3.1 Hinze et al. (1956)

The Hinze et al. (1956) paper is specific to a fall Chinook salmon stock of the American River, California. The authors' main question centered on whether egg incubation at the newly constructed Nimbus Hatchery would be adequate when operational water was provided from a new upstream reservoir. Hinze et al. (1956) reports on the first year of Nimbus Hatchery operations. The upstream reservoir from where their operational water originated had just been filled during the previous months for the first time. There was no formal experiment conducted and reported on in this report; this was an annual hatchery operation report. Aside form potential elevated temperature problems, it was noted that several other water quality problems within the hatchery persisted throughout the incubation period, including: reduced dissolved oxygen through mid-November, elevated sulfides (which at very low levels are toxic to developing embryos), gas super-saturation, and increased turbidity. Early egg-take lots suffered elevated mortality, and this was attributed solely to elevated temperature during adult maturation and the egg-take period. This conclusion was determined only from discussion among various hatchery personnel and not from "scientific" testing. Further, while the authors concluded that elevated water temperature during adult holding was the primary factor for increased embryo mortality, they also stated, "***No facts have been gathered to back up this supposition***". As such, this report should not be cited as evidence leading to conclusions for decreased gamete viability relative to water temperature. The other water quality problems, other than gas super-saturation, were not considered as potential causes to mortality. The egg-lots that are reported as suffering the highest mortality were spawned at water temperatures ≥16.7°C. There is no data presented in the report pertaining to mortality within individual egg lots.

When comparing the maximum daily water temperature data provided in Hinze et al. (1956) to what is generally observed within the Snake River during the fall Chinook salmon spawning period (Figure 6), it is evident that the conditions of the Nimbus hatchery are not comparable to the Snake River. Adult holding temperatures (estimated for 5 October -25 October in this report) averaged 20.0°C (with a relatively stable range between 20.6-19.4°C) at Nimbus Hatchery, compared to 16.9°C (with a declining range between 18.4-15.4°C) for the same time period in the upper Hells Canyon Reach (the warmest area during the fall period) of the Snake River. As well, water temperature at the Nimbus Hatchery during the fall of 1955 remained ≥16.5°C through 10 November, by which time the peak of spawning had occurred. This is in stark contrast to water temperatures in the upper Hells Canyon Reach of the Snake River that generally drop below 16.5°C by about 20 October. While the water temperatures in both systems drop at similar rates from early October through late December, water temperatures at the Nimbus Hatchery averaged 3.3°C warmer (range 1.4-5.1°C) than the upper Hells Canyon Reach of the Snake River. It is certainly possible that elevated water temperature at the Nimbus Hatchery during adult holding (averaging 20.0°C for at least 20 days just prior to spawning), and remaining elevated above 16.5°C through early incubation and peak spawning (an additional 15 days), could have been factors contributing to increased embryo mortality. However, this is not a situation comparable to that of the Snake River.

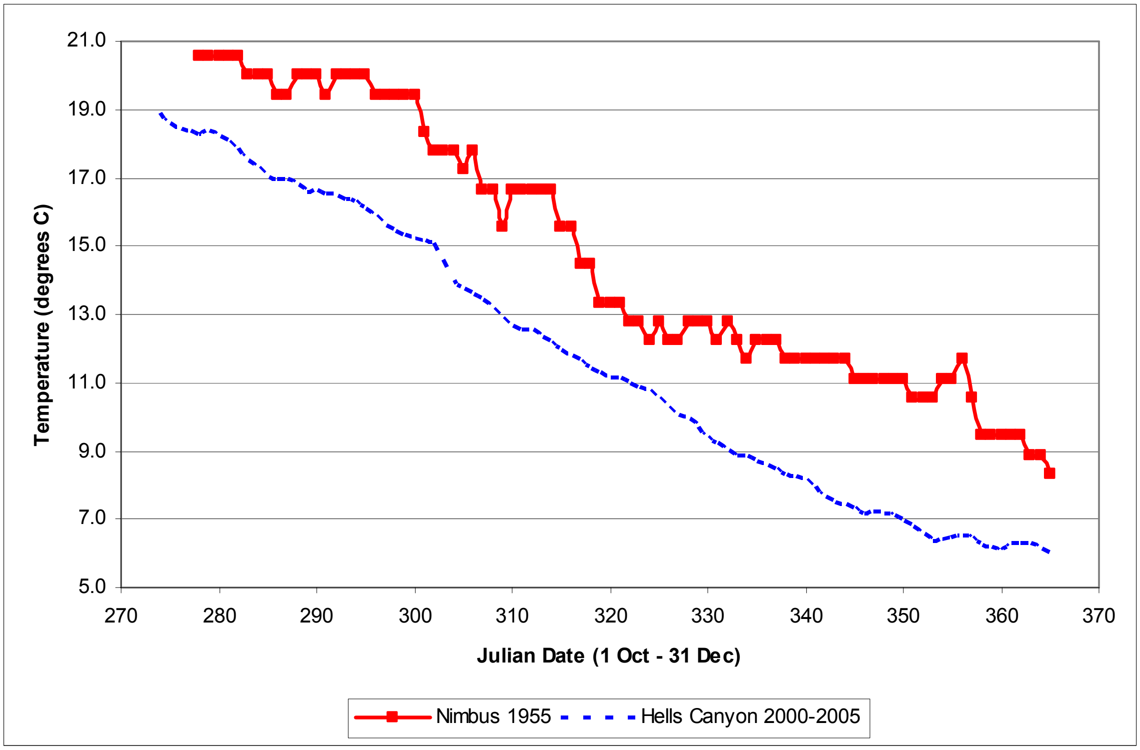

Figure 6. Comparison of maximum daily water temperature reported for Nimbus hatchery (1955) and the mean daily maximum temperature in the upper Hells Canyon Reach of the Snake River (2000-2005).

4.3.2 Hinze (1959)

The Hinze (1959) paper is also specific to fall Chinook salmon of the American River, California. Again, the main question discussed in this paper was whether egg incubation at the Nimbus Hatchery was feasible when operational water was provided from an upstream reservoir. Hinze (1959) reports on the third year of Nimbus Hatchery operations. While this was also an annual hatchery report, there was an attempt to conduct a formal experiment on adult holding temperatures and potential effects to gamete success. Adult Chinook salmon from the American River were able to be maintained at the Nimbus Hatchery for about 10 days prior to mortality when water temperatures were between 15.0-19.4°C, while adults transported to Kyburz (a cold-water holding base) could be kept alive for about 6 weeks at temperatures between 4.4-10.0°C. However, while adult Chinook salmon could be kept alive at the lower temperature, their gametes did not ripen and they had to be returned to Nimbus Hatchery and placed in warmer water (13.6-14.4°C) to allow their gametes to ripen. Eggs finally taken from the Kyburz-held fish were subjected to several spawning and incubation environments. Results are as follows:

1. Eggs spawned and incubated at water temperature ≥16.7°C suffered 100% mortality;
2. Eggs spawned and incubated at water temperatures between 15.6-16.7°C suffered 50% mortality to the eyed stage;
3. Eggs spawned and incubated at water temperatures between 12.8-13.3°C suffered 20% mortality to the eyed stage;
4. Eggs spawned between 15.6-16.7°C and then incubated at temperatures between 12.8-13.3°C suffered 30% mortality to the eyed stage;
5. Eggs that were spawned and incubated at water temperatures between 1.1-3.3°C suffered 100% mortality.

While these results are interesting relative to spawn and incubation temperatures, they are not applicable to the question of gamete viability as a result of pre-spawn exposure to elevated water temperatures.

In an effort to establish a new strain of Chinook salmon at the Nimbus Hatchery, 51 adults (15 male and 36 female) were transported to the Nimbus Hatchery from the Klamath River. These fish were on-station at Nimbus Hatchery by 29 September, when the daily maximum water temperature was 18.1°C and rising. By 22 October, only 7 (5 males and 2 females) of the original 51 Klamath River test adults remained alive. The mean daily maximum water temperatures during that 24-day holding period had been 18.9°C (range of 18.1-19.4°C). Only one of the Klamath River females was able to be spawned, on 22 October, at a temperature of 18.3°C. As a comparison, a single American River female was spawned on the same date, at the same temperature. Both groups of eggs attained the eyed stage on 11 November. The mean daily maximum water temperature from 22 October through 11 November was 17.8°C (range of 16.4-19.2°C). Only 16% of the American River eggs and 35% of the Klamath River eggs survived to the eyed stage. Through the rest of the incubation period, only 1.3% of the American River and 16% of the Klamath River eggs survived to the hatch stage. No fry were maintained past 26 February, when only 6 individual Klamath River fry remained alive. Conclusions relative to prespawn temperature conditions and gamete viability cannot be reached from this evaluation because of the confounding factors of high temperature during the incubation period to the eyed stage. Both stocks performed poorly from a sample size of one female from each group.

Comparing the water temperature data provided in the Hinze (1959) report to what is generally observed within the Snake River when fall Chinook salmon spawn (Figure 7), shows that adult holding temperatures (estimated as 1-22 October for this report) averaged 18.9°C (with a fairly stable range of 19.6-18.1°C) at Nimbus Hatchery, compared to 17.4°C (with a declining range between 18.9-16.1°C) for the same time period in the upper Hells Canyon Reach of the Snake River. As well, water temperature at the Nimbus Hatchery during the fall of 1957 remained ≥16.5°C through 11 November. This is in stark contrast to water temperatures in the upper Hells Canyon Reach of the Snake River which generally drop below 16.5°C by about 20 October. During the 1957 fall season, the water temperature at the Nimbus Hatchery declined at a rate of 0.1°C per day, in contrast to the rate of decline normally observed in the Snake River of about 0.2°C per day. As well, water temperatures at the Nimbus Hatchery averaged 3.8°C warmer (range 0.3-6.2°C) than the upper Hells Canyon Reach of the Snake River throughout the period 1 October through 31 December. It is possible that elevated water temperature at the Nimbus Hatchery during adult holding (averaging 18.9°C for at least 22 days just prior to spawning), and remaining elevated above 16.5°C through early incubation and peak spawning, was a factor contributing to increased embryo mortality. However, this report is not a good citation to support the effects of elevated water temperature on gamete viability because of the confounding factors of high temperature during the incubation period to the eyed stage nor, because of the significant differences in temperature data is it useable to compare with conditions relative to the Snake River and fall Chinook salmon.

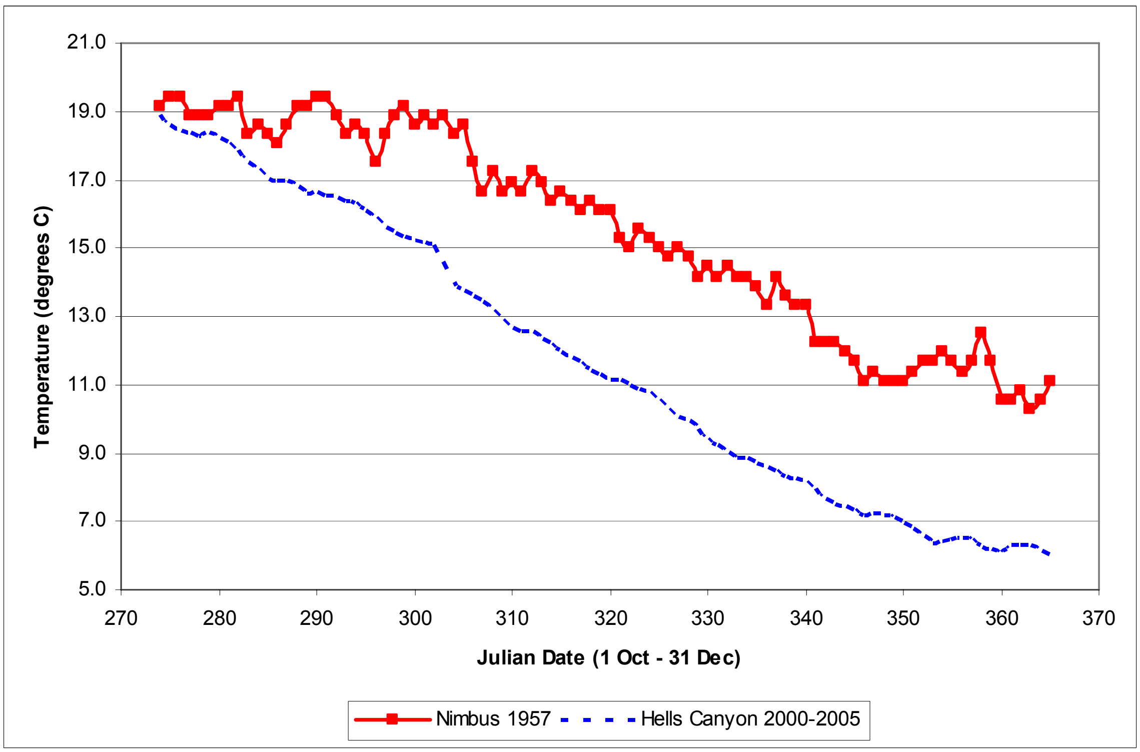

Figure 7. Comparison of maximum daily water temperature reported for Nimbus hatchery (1957) and the mean daily maximum temperature in the upper Hells Canyon Reach of the Snake River (2000-2005).

4.3.3 Rice (1960)

The Rice (1960) report is also specific to fall Chinook salmon of the American River, California. The main question discussed in this paper was whether delayed embryo mortality at the Nimbus Hatchery was a direct result of elevated water temperature (≥15.6°C). An attempt was made to conduct an experiment; however, it is difficult to determine the actual conditions during the pre-spawn, spawn, and incubation phases being tested in the experiment.

In this experiment, adult Chinook salmon were trapped in the American River and hauled to the Bear River cold-water holding station. There were three groups of eggs from which data were collected, and embryos were only maintained through the eyed stage. One group was spawned at Bear River and were incubated through the eyed stage at Bear River, a second group was spawned at Bear River and were then transferred to, and incubated to the eyed stage at, Nimbus Hatchery, and the third group was spawned at Nimbus Hatchery and then taken to and incubated through the eyed stage at the Bear River station. The results were that the eggs spawned and incubated at Bear River (adults held and spawned and eggs incubated in cold water) had a 53.9% survival to the eyed stage, the eggs spawned at Bear River and incubated at Nimbus Hatchery (adults held and spawned in cold water and eggs incubated in warm water) had a 35.4% survival to the eyed stage, and the eggs spawned at Nimbus and then incubated at Bear River (adults held and spawned in warm and eggs incubated in cold water) had a 41.3% survival to the eyed stage.

Unfortunately, there is no description of the actual thermal regime that pre-spawn adults were exposed to, at what temperature eggs were spawned at, or the thermal regime that each egg group was subjected to. Also, because the eggs were apparently maintained as one large group in each treatment, there is no way to statistically analyze the results. Finally, other circumstances (other than water temperature) are referred to that caused embryo mortality, including: smothering, fungus growth, and exposure to direct sunlight. In the end, the results from this report are inconclusive relative to the question of pre-spawn exposure to elevated water temperatures and gamete viability.

4.3.4 Jewett and Menchen (1970)

The Jewett and Menchen (1970) report is specific to a fall Chinook stock from the Mokelumne River, California. This report describes the artificial spawning channel (and its maintenance and operation) on the Mokelumne River, as well as an incubation survival test conducted in the hatchery building. Adult Chinook salmon were allowed to enter and remain in an artificial spawning channel having a gravel bottom and water running through it that was diverted from the Mokelumne River. The water temperature in the channel was equal to what was observed in the Mokelumne River. Adult salmon were allowed to spawn naturally in the channel, their carcasses were collected afterward, and an estimate was made as to the number of eggs deposited in the gravel. After juveniles emerged, they were captured in a downstream trap and enumerated as they emigrated from the channel; the managers estimated production from the resulting juvenile numbers and estimate of deposited eggs. This report also details a specific test that was performed in order to learn more about how elevated water temperature during early spawning may have affected the survival of later developing embryos.

During the test (in the fall of 1966), 12 female Chinook salmon were spawned, and their eggs were maintained in the hatchery building. The eggs were split into three groups and were maintained in different thermal regimes. Resulting fry were maintained through feeding and the survivors were planted into the Mokelumne River in May of 1967. There are no dates provided for the spawn-timing of the females, and the actual thermal regime experienced by pre-spawn adults and each egg group is not provided. The only details provided are as follows:

1. Eggs from three females were spawned at temperatures between 13.9-15.6°C; eggs from one of the females were too green and they all perished; eggs from the other two females resulted in final fry survival of 72.2%.
2. Eggs from three females were spawned at 14.4°C; the final fry survival was 74.5%.
3. Eggs from six females were spawned at temperatures between 12.2-12.8°C; eggs from one of the females were too green and they all perished; eggs from the remaining females resulted in final fry survival of 84.6%.

Because of the way the samples were produced and maintained, it is not possible to statistically analyze the results from this test, and the differences observed may not represent statistical differences. The authors concluded that water temperature during early spawning resulted in elevated mortality of developing embryos. It is more likely that elevated water temperature throughout the greater part of early embryo development (the first three weeks of November) was a more reasonable explanation for the observed mortality. Figure 8 demonstrates that for a brief period, water temperatures during the early incubation exceeded 17°C in this study. Geist et al. (2006) demonstrated that for periods less than the exposure in this study to water temperatures of 17°C caused significant mortality. Regardless, this study should not be cited as an evaluation of gamete viability relative to pre-spawn temperature exposure.

A comparison of the maximum daily water temperature data provided for the Mokelumne River in the Jewett and Menchen (1970) report to what is generally observed within the upper Hells Canyon Reach of the Snake River when fall Chinook salmon spawn (Figure 8) again shows very different thermal regimes between these rivers. The daily maximum mean water temperature within the Snake River (16.7°C) is typically warmer than what was reported for the Mokelumne River in 1966 (16.2°C) during the adult holding period (roughly 1-31 October). However, while the Snake River thermal regime typically declines from about 18.9°C to 14.0°C during this period, the Mokelumne River temperature tended to ***increase*** from 15.6°C to 17.2°C. Also, water temperature in the Snake River tends to average 11.3°C during November (with a declining regime from about 14.0°C to 9.0°C), while the Mokelumne River averaged 15.1°C (with a slightly declining regime from about 16.0°C to 14.5°C). It is reasonable to conclude that within the Mokelumne River elevated incubation temperatures throughout the entire month of November would have had a significantly negative effect on embryo survival.

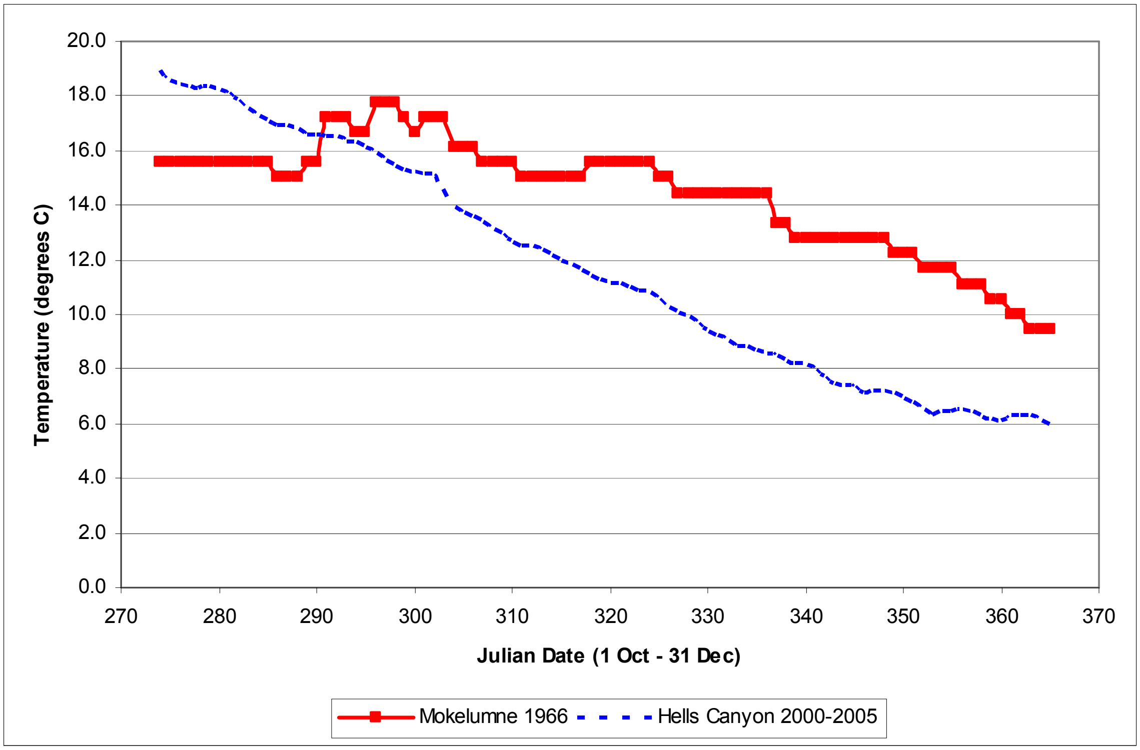

Figure 8. Comparison of maximum daily water temperature reported for the Mokelumne River (1966) and the mean daily maximum temperature in the upper Hells Canyon Reach of the Snake River (2000-2005).

4.3.5 Jewett (1970)

The Jewett (1970) report is also specific to fall Chinook salmon of the Mokelumne River, California. Low estimated production in previous years was thought to have resulted from elevated water temperature (approximately 15.6-16.1°C) during pre-spawn holding. The managers hypothesized that the warm holding temperatures were harming the developing eggs within the females. Therefore, during the fall of 1967, an incubation test was performed. Unfortunately, there is little detail as to the experimental design of the study. Four females were spawned with four males, and the fertilized eggs were maintained in a hatchery building. However, there is no information as to the dates when the gametes were fertilized or of the actual water temperatures at the time of spawning. It is noted that at the time of spawning, eggs from the females were in various stage of development, from too green to over-ripe. It is also mentioned that the water temperature did not drop below 15.6°C until 16 days after the eggs were fertilized. Based on the limited information provided in the narrative, and the daily record of water temperature provided in the appendix of the report, it appears that spawning took place during the second week of November, when water temperatures were between 16.1-16.7°C. From the total number of test eggs that were able to be fertilized, 67% survived to the hatch stage, and 28% of the total survived to the planting stage.

The main conclusion derived from the experiment was that elevated water temperature during adult holding (pre-spawn) was the reason for depressed survival of embryos through the planting stage. However, the data presented do not support this conclusion. The author did not consider the possibility that maintaining the fertilized embryos at fairly constant, elevated temperatures for a lengthy period (≥15.6°C for 16 days) may have been a cause for elevated embryo mortality.

As with the Nimbus Hatchery evaluation (Hinze et al. 1956, Hinze 1959, Rice 1960), it is interesting to compare the plots of the maximum daily water temperature data provided in the Jewett (1970) report to what is generally observed within the Snake River when fall Chinook salmon spawn (Figure 9). The mean daily maximum temperature during the estimated adult holding period (1-31 October) for the Mokelumne River was lower (15.2°C) than what is generally observed in the upper Hells Canyon Reach of the Snake River (16.7°C). However, the thermal regime in the Mokelumne River ***increased*** during that period, from a low of 13.9°C to a high of 16.1°C, as compared to the Snake River, which typically declines from 18.9°C to 14.0°C. The most noticeable difference in the thermal regimes of the two rivers is that the Mokelumne River remained relatively stable and ≥15.0°C throughout the period 8 October through 29 November, while the Snake River is characterized by a continuously declining regime that is typically at 18.1°C on 8 October, drops below 15.0°C by 30 October, and by 29 November is just below 9.0°C.

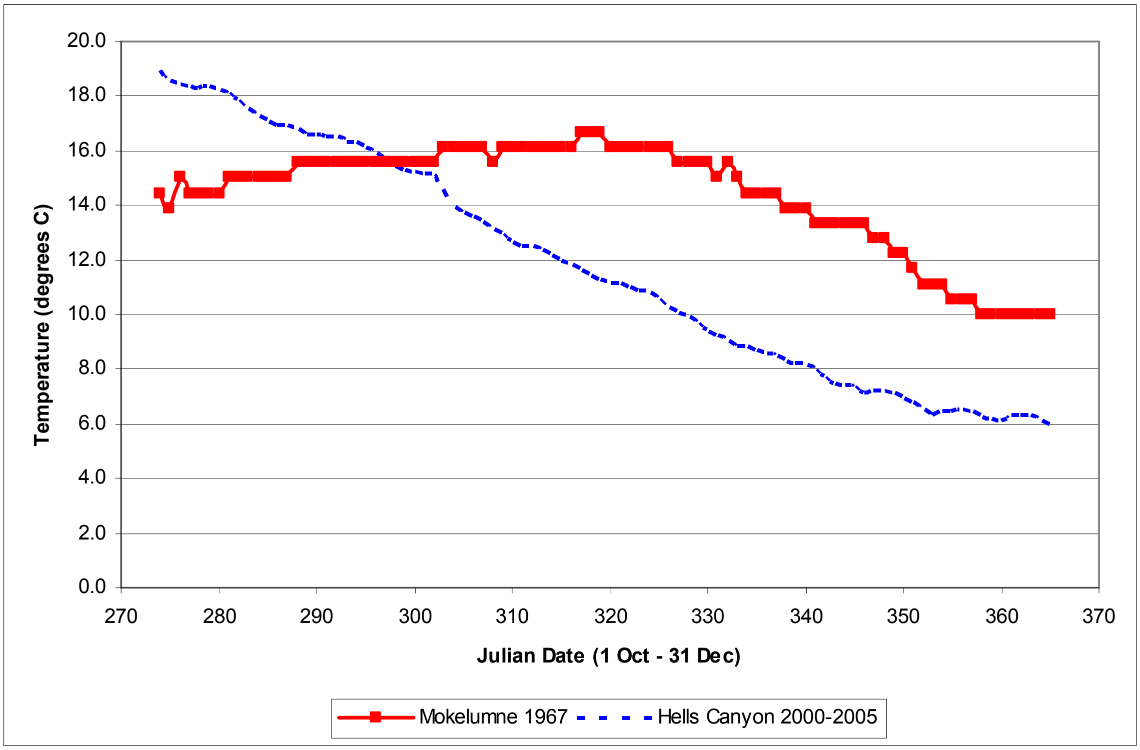

Figure 9. Comparison of maximum daily water temperature reported for the Mokelumne River (1967) and the mean daily maximum temperature in the upper Hells Canyon Reach of the Snake River (2000-2005).

4..3.6 Berman and Quinn (1989)

This report is an annual progress report of a University of Washington Masters' thesis. This report discusses a pilot project that was conducted in order to test the feasibility of holding adult Chinook salmon at two different, fairly constant, water temperatures over an extended period prior to spawning. It was hoped in the original design that adults could be held at the two temperatures and spawned afterward; the embryos would then be maintained through development in order to determine if elevated water temperature during holding affected reproductive success. The fish used in this test were spring Chinook salmon from the Kalama Falls State Hatchery. The results from this pilot project are often cited in support of reproductive success being reduced due to elevated adult holding temperature (e.g. McCullough et al. 2001), contrary to the following admonition of the authors: **"Interpretation of results from the pilot study were complicated by the presence of several confounding variables. Thus, when reviewing data derived from the pilot study it is imperative that differences between the treatment groups not be attributed solely to temperature."** The authors also conclude: **"… it is difficult to determine from the records whether mortalities were related to temperature or other variables such as disease outbreak or sediment load that may affect egg survival."**

Initial test fish entered the hatchery by 3 August and were maintained on-station until 30 August. Twenty females were selected and tagged, split into two groups of ten, and then transferred into two different holding environments. Ten females were maintained in a cold environment at a local spring and experienced fairly constant water temperatures between 4.4-6.0°C. The other ten females were kept at the hatchery and were placed in a pond with the rest of the hatchery fish; these fish would have experienced water temperatures between 10.0-16.7°C. All fish used for the pilot study were spawned during the first week of September. The following observations are noteworthy:

1. At the time of spawning, all of the originally tagged females in the hatchery (warm-water group) had shed their tags, and new females with unknown thermal histories had to be chosen.
2. A fungal infection ran rampant through the cold-water control group of females, and only four remained alive at the time of spawning.
3. After spawning a portion of the eggs was maintained at the University of Washington at constant 9.0°C and a portion was maintained at the hatchery at an undisclosed temperature.
4. Eggs kept at the university were maintained through the hatch stage, while eggs at the hatchery were kept through the eyed stage.
5. Average mortality through the eyed stage was 8% for eggs from the warm-water females, and 36% for the eggs from the cold-water females.
6. Both treatment groups showed similar mortality rates through hatching.

In sum, this report provides no evidence that elevated pre-spawn holding temperatures, as high as 16.7°C, result in reduced viability of Chinook salmon gametes.

4.3.7 Berman (1990)

This document is a completed Masters' thesis from the University of Washington, and is tied directly to Berman and Quinn (1989). The main study species is spring Chinook salmon of the Yakima River. The actual thesis has three separate main objectives:

1. Determine if elevated pre-spawn holding temperatures negatively affect Chinook salmon gamete viability.
2. Determine if pre-spawn Chinook salmon in the wild can behaviorally regulate their internal body temperature to alleviate exposure to elevated water temperature.
3. Model Yakima River water temperatures in order to determine the extent of degradation potentially caused by stream-bank logging, and whether mitigation actions might be able to restore the historic thermal regime.

The results from the first main objective are often cited to support the proposition that elevated water temperature during pre-spawn adult holding has a significant, negative effect on Chinook salmon gamete viability. For the first objective, 33 adults were trapped at Roza Dam and transferred to Priest Rapids Hatchery on the Columbia River. The holding test began on 26 June. These fish were split into two almost equal groups. Until 7 July, all fish were maintained at about 14.0°C. Afterward, one group (control) was kept at about 14.0°C (range 14.0-15.5°C), and the second group (test) was kept at about 19.0°C (range 17.5-19.0°C). The experimental design was to keep all fish alive and spawn them; however, by 20 August (45 day period) all but two of the test fish had perished. The two remaining fish were males. Therefore, the control group was then split to produce one new control and two new test groups. The new control group continued to be maintained at about 14.0°C, and both of the new test groups were maintained at about 19.0°C. Both test groups were maintained at about 19.0°C through 4 September (15 day period). Spawning of all fish took place from 18 September through 3 October. Unfertilized gametes were collected at Priest Rapids, transferred to the University of Washington, and were then mixed. Five hundred eggs from each female were kept; this resulted in a total of 1000 eggs from the control group, 1500 eggs from test group one, and 1000 eggs from test group two. All eggs were maintained at a constant 9.5°C throughout incubation. Because of the way the eggs were grouped, it was impossible to statistically analyze the results. **All embryos (control and test) perished within 24 hours post-hatch.** This unfortunate event makes it difficult to scientifically accept the value of any of the results stemming from this part of the study. Prior to 100% mortality, there had been 1 pre-hatch mortality in the control group (0.1% mortality), 12 pre-hatch mortalities in test group one (0.8% mortality), and 9 pre-hatch mortalities in test group two (0.9% mortality). The size and weight of the test alevins appeared to be less than the control alevins, but this could not be statistically validated.

The results from the first objective of this thesis are scientifically unsound, and do not support the hypothesis that elevated temperature during adult holding results in decreased gamete viability. However, results do suggest that if spring Chinook salmon adults remain at constant temperatures of about 19.0°C for 45 days, they will perish, but that 15 days at that temperature will not result in elevated pre-spawn mortality.

4.3.8 Jensen et al. (2005)

This study used summer Chinook salmon from the Puntledge River on Vancouver Island, British Columbia, Canada. It was undertaken because there was concern that elevated water temperature experienced by the natural population in the Puntledge River might be causing increased mortality, especially with respect to gamete viability due to adult pre-spawn temperature exposure.

All adults used for this study were captured during the summer of 2003 and held on-station until spawning that fall. Adults were maintained in six circular holding tanks under similar densities, and were provided with similar water circulation and dissolved oxygen saturation conditions. Two tanks were maintained at ambient temperatures for the Puntledge River, two were exposed to temperature conditions that were elevated over the ambient regime, by about +2.0°C, and two were maintained at temperature conditions that were chilled by about -2.0° below the ambient regime.

The authors noted that an anomalous event occurred around mid-September (when water sources were altered), resulting in 100% mortality of females and 58% loss of males in the ambient temperature group of adults. They stated that this event was sudden and had nothing to do with the ambient water temperature.

The only comparison that could be attempted at that point was between the chilled and heated group of fish. Both females and males within the heated group experienced elevated pre-spawn mortality when compared with the chilled group. Female pre-spawn mortality was 83% for the heated group compared to 36% for the chilled group. Male pre-spawn mortality was 33% for the heated group compared to 8% for the chilled group. These were statistically significant differences. The authors noted that maturation tended to occur later for the heated group (mean of 8 November) as compared to the chilled group (mean of 18 October). This was not a statistically significant difference.

Eggs from females of both groups were taken and immediately maintained under what the authors considered good to excellent thermal conditions for incubation. A statistical test of difference between mortality in the chilled and heated groups was not attempted; however, it is possible to accomplish this because of the way the eggs were maintained. The authors noted that the quality of gametes from all test subjects, both chilled and heated, appeared to be in very good condition, and that this was very different from what was observed with pink salmon during a previous study (Jensen et al. 2004). Embryos for each group were maintained through the ponding stage (past emergence). Final embryo mortality for the chilled group was 5.1% compared to 1.5% for the heated group. There was no statistically significant difference in final embryo mortality.

Additionally, the authors collected data on egg size prior to spawning. They did not attempt to statistically test whether a difference existed between the chilled and heated groups; however, they did note that there did not appear to be a difference.

The authors concluded several times that the results with Chinook salmon were very different from what they observed for pink salmon (Jensen et al. 2004). Egg quality was observed to be degraded in pink salmon, especially in the heated groups, while this was not the case for Chinook salmon. Final embryo mortalities in the pink salmon tests were higher for both chilled (13.5%) and heated (60.2%) groups as compared to Chinook salmon.

4.3.9 Jensen et al. (2006)

This study was an attempt to reproduce the 2003 work (Jensen et al. 2005). The study species again was the Puntledge River summer Chinook salmon.

The entire experimental design was modified relative to the 2003 evaluation, and it is difficult to compare results from the two studies. Several different groups were maintained during this study: one group was split and held in the chilled, ambient, and heated temperature tanks as in the previous work, one group was collected and held in a raceway at the upper Puntledge River Hatchery site, one group was collected and held at a raceway at the lower Puntledge Hatchery site, and a final group was collected at Puntledge, and transported and held in a large tank at the Rosewall Hatchery. The fish held in both the upper and lower Puntledge Hatchery raceway sites were exposed to ambient Puntledge River water temperatures. The fish held at Rosewall were supplied with fairly constant temperature (7.8 – 9.0°C) spring water.

The objective of the experiment was to test for differences in pre-spawn mortality in the chilled, ambient, and heated tanks at Puntledge Hatchery, to test for differences in spermatocrit values across all exposure groups, and to test for embryo mortality across all pre-spawn temperature exposure groups. Embryos were incubated at a constant temperature of 12.0°C, and were only maintained through the hatch stage.

A change in operations at the upstream hydroproject affected water quality in the Puntledge Hatchery holding tanks, and this led to early, complete mortality of all female adults in the chilled, ambient, and heated temperature tanks by 1 September. A graphic of mortality by date indicates that total mortality occurred in the chilled group first. However, the researchers noted that the change in upstream dam operations mobilized large amounts of sediment and silica-algae in the main river, which was entrained through the experimental tanks. They believed that complications due to the increased sediment load resulted in severe irritation to gill membranes, which led to the massive loss of fish in all Puntledge Hatchery experimental tanks.

Fish in the upper and lower Puntledge River Hatchery raceways and in the Rosewall Hatchery pond were ultimately spawned, and comparisons were made between those three groups. It is very important to understand that fish in the Puntledge Hatchery raceways were not able to seek out thermal refugia (as fish in a natural environment might be able to do) and they were continuously exposed to elevated water temperatures (>19.0°C) for approximately 40 days. In contrast, the Rosewall fish were exposed to water temperatures that fluctuated between only 7.8-9.0°C, a condition not normally present in a natural river system.

Pre-spawn mortality of females in the upper and lower Puntledge Hatchery raceways could not be definitively calculated because the initial number of fish in the raceways was unknown, and there was a reported high loss of adults to predation. However, relative mortality calculated for females on hand at the time of spawning was 46% for both Puntledge sites combined, while the Rosewall group experienced 8% mortality.

The maturation rate of gametes was noted as being similar across both Puntledge Hatchery and Rosewall groups of fish. This was different than what was observed for Chinook salmon during the 2003 trials.

Spermatocrit values averaged 40% (Rosewall), 36% (lower Puntledge), and 28% (upper Puntledge). Rosewall and lower Puntledge values were statistically similar, while the upper Puntledge value was determined to be statistically lower than the other two. However, the authors concluded that this was not biologically significant, as eggs from

Rosewall were fertilized with milt from males held at both Rosewall and the upper Puntledge site, and no difference was detected in the survival of those embryos.

Embryo mortality through the hatch stage was similar between the two Punteldge Hatchery groups (11.8% and 13.4%), but was statistically higher than what was observed for the Rosewall group (3.1%). Again, it was noted that these values were different than what was observed for pink salmon during an earlier experiment (Jensen et al. 2004).

The average egg weight was lowest for the females held at the Rosewall site; however, there was no statistical significance across the three groups.

These final two studies conducted by Jensen et al. (2005) and Jensen et al. (2006) appear to be the best information presently available concerning how elevated water temperature during holding can result in increased pre-spawn mortality, as well as how gamete viability may be affected if adults are maintained for long periods of time at elevated temperatures. It is important to understand that these studies (like Berman 1990) held adults at elevated water temperature (>19.0°C) for an extended period of time, approximately 40 days, prior to spawning. Also, while one of the studies indicates that no differences in gamete viability occurred between a chilled and heated thermal group of fish, the second one did show that gamete viability was statistically different between groups of females exposed to different thermal environments. However, the test that showed differences held females at constant, low temperatures (which would not occur in a natural river environment), and compared the viability of their gametes with fish held in a naturally occurring thermal environment of a river. While this test did result in differences in gamete viability, it is uncertain if the 12-13% embryo mortality would represent an expected range for natural spawning adults in a more normative river environment as compared to the low constant temperatures to which the data were compared. Finally, the authors noted several times throughout these two papers that results for Chinook salmon and pink salmon (Jensen et al. 2004) were very different, and it would be unwise to view the two species as functional equivalents.

After review of these commonly cited studies relative to gamete viability, it appears that only the Jensen et al. (2006) evaluation supported the hypothesis that gamete viability can be affected by pre-spawn water temperature conditions. However, it remains unclear whether elevated water temperature during the pre-spawn adult holding period under a declining natural thermal regime would result in negative effects to embryonic development in Chinook salmon. Certainly, prolonged exposure (40 days in these experiments) of adult spring Chinook salmon to elevated water temperatures does appear to result in elevated pre-spawn mortality and in the case of Jensen et al. (2006) may affect gamete viability. Snake River fall Chinook currently do not face the extreme conditions used in the Jensen et al. (2006) study. Clearly, more research is needed in this area to determine the differences relative to the length of exposure to elevated water temperature and gamete viability under a thermal pattern that represents the declining thermal regime of a fall spawning fish.

4.4 Disease Susceptibility

It is common knowledge that disease effects can become exacerbated in Chinook salmon adults when they are exposed for prolonged periods of elevated water temperatures in the pre-spawn environment, especially when they are held in close, confined, stressful quarters (such as hatchery ponds and raceways). However, as discussed above under pre-spawn mortality, the thermal environment of the lower Snake River today is cooler during the early portion of the adult migration period (through about the end of September). The temperature presently drops below the 20°C criteria established for protecting adult migrating anadromous salmonids at a time that is comparable to historic conditions. After the river cools below 20°C the rate of cooling is not as rapid today as it was prior to the construction of the Hells Canyon Complex, but the water temperature remains below the protective criteria. There is no evidence of major disease outbreaks occurring in the natural population of returning adult fall Chinook salmon that presently migrate upstream past the four lower Snake River dams. This is supported by the low fish to redd ratios observed in the Snake River Basin (discussed earlier), which do not indicate that problems due to disease or pre-spawn mortality in general in the natural population upstream of Lower Granite Dam is of concern.

4.5 Spawn Timing

Elevated water temperatures can affect physiological and physical processes such as the rate of gamete maturation within adults or potentially suppressing an environmental cue such as that associated with the process of redd construction and spawning. For the Snake River below Hells Canyon and other rivers such as the Grande Ronde and Clearwater, there are several years of empirical data on spawning activity of Snake River fall Chinook salmon and corresponding water temperature information. There are also some data available on historic spawn timing prior to the construction of the Hells Canyon Complex. These data can be used to help further examine if spawn time has changed and potentially help examine the feasibility of altering spawn-timing by manipulating water temperature.

Several researchers have attempted to maintain adult Chinook salmon at elevated water temperatures prior to spawning. Berman (1990) maintained adult spring Chinook salmon at constant test and control temperatures of approximately 19°C and approximately 14°C (respectively) for approximately two weeks prior to spawning. From her descriptions, there appeared to be no delay in gamete maturation in the fish maintained at the elevated test temperature. Jensen et al. (2005) maintained adult summer Chinook salmon at two different test temperatures that followed a normal, local river thermal regime. The two test thermal regimes were kept approximately 2.0°C warmer and colder than the ambient river temperature. The warm group was subjected to temperatures ≥19.0°C for 42 days (with a maximum mean temperature of 22.8°C). The cool group experienced a maximum temperature of only 18.3°C). This is a substantial difference in thermal environments.

The authors noted that the warm group had later gamete maturation timing than did the cooler group, approximately a three week difference. However, only two females remained alive in the heated group, and it is possible that these could have just been late maturing fish, and water temperature had nothing to do with the gamete maturation differences observed. As well, the authors reported that the gametes from the two fish of the warm thermal test group had gametes of good quality, which was obviously different than what had been observed for pink salmon in an earlier experiment (Jensen et al. 2004). Jensen et al. (2006) again maintained summer Chinook salmon at two different thermal regimes prior to spawning. Their control group was maintained at a fairly constant temperature of approximately 9°C. Their test group of Chinook salmon was maintained at ambient river temperatures; these test fish experienced temperatures ≥19.0°C for about 40 days (with a maximum mean temperature of 22.0°C). The ambient test group of this experiment experienced a similar thermal regime as the fish from the heated test from the previous experiment. Results were very different from what was observed during the previous experiment; no difference was observed in the rate of gamete maturation between the control and test groups. Maturation of gametes occurs over a protracted time period, as represented by the protracted range of natural spawning observed. For example, Zimmer (1950) reported fall Chinook salmon to spawn from late September to early December in the Snake River upstream and prior to construction of the Hells Canyon Complex.

Within the Snake River, adult fall Chinook salmon can pass into and hold within several different river reaches, all having different thermal characteristics. As well, if adult fish within the Snake River are experiencing less than optimal water temperature, they have the ability to freely move among the various reaches and seek out thermal refuges. Fish held for experimental or cultural purposes of course do not have the ability or freedom to seek out thermal refuges unless this was specifically provided in the experimental design. If migrating adult fall Chinook salmon were to remain in the vicinity of Ice Harbor Dam (close to the mouth of the Snake River), it is conceivable that they could be exposed to temperatures ≥19.0°C for about 46 days (with a maximum mean temperature of about 22.0°C). However, as has been discussed earlier, migrating adult salmon have been observed to quickly move through these areas (Peery et al. 2003). Similarly, if adult fall Chinook salmon remained in the vicinity of Lower Granite Dam, it is conceivable that they could be exposed to temperatures of approximately 19°C for about 28 days (with a maximum mean temperature of about 18.5°C). It generally takes adult salmon only a couple of days to navigate through the Lower Granite Reservoir and into the vicinity of the lower Clearwater River and the lower Hells Canyon Reach of the Snake River. It may only take a few days longer to move upstream into the upper Hells Canyon Reach of the Snake River. Fish moving into the Clearwater River (where spawning has been observed to start earlier than in the Snake River) would immediately experience significantly cooler temperatures (generally a maximum of approximately 15°C). Near the confluence of the Snake and Clearwater rivers, there is a significant cool water refuge available for upstream migrating adult fall Chinook salmon, largely because of the cooling effect of releasing water from Dworshak Reservoir. The ***earliest*** fish entering the lower Hells Canyon Reach of the Snake River could conceivably experience water temperatures ≥19.0°C for about 32 days (with a maximum mean temperature of about 22.0°C). Again, if these fish experience thermal stress, they could move back downstream into a more amenable thermal refuge near or in the Clearwater River, or could even continue moving upstream into areas where other thermal refuges exist. For example, water entering the Snake River from the Grande Ronde River (Snake RM 168) tends to be <19.0°C by 1 September, and is cooling rapidly. There are also similar cool water refuges further upriver near the mouths of the Salmon and Imnaha rivers, and at many other smaller tributaries throughout the upper Hells Canyon Reach (such as Divide Creek, Zig-Zag Creek, Wolf Creek, Deep Creek, Getta Creek, Tryon Creek, Camp Creek, Sommers Creek, Kirby Creek, Kirkwood Creek, Temperance Creek, Sheep Creek, Rush Creek, Sluice Creek, Bernard Creek, Hat Creek, Saddle Creek, Three Creeks, Granite Creek, Wild Sheep Creek, Battle Creek, Brush Creek). If the earliest migrating adult fall Chinook salmon were to be immediately transported to and remain in the warmest water of the upper Hells Canyon Reach of the Snake River, they might be exposed to temperatures ≥19.0°C for about 45 days (with a maximum mean temperature of about 22.0°C). This is similar to what fish used by Jensen et al. (2006) experienced, and they did not report a delay in gamete maturation, or in quality of gametes. However, it is unknown whether adult fall Chinook salmon tend to immediately move into the upper Hells Canyon Reach, or the extent to which they may use cool water refuges mentioned above.

With respect to delay of the actual spawning activity, there is evidence that a shift toward earlier spawning might be feasible if the river corridor could be cooled substantially. However, it would likely be very difficult to cool the river enough to make a reasonable shift in spawn timing. Data from 16 years of spawning surveys in the Snake River indicates that initial spawning is not consistently initiated because of either photo period or water temperature (Table 3). In the upper Hells Canyon Reach, the earliest spawning was observed as early as 9 October (at a weekly mean temperature as high as 19.1°C), and as late as 11 November (at a weekly mean temperature as low as 12.5°C). This presents a difference in timing of four weeks and a 6.5°C difference in temperature. In the lower Hells Canyon Reach (LHC), spawning was observed as early as 9 October (at a weekly mean temperature as high as 17.9°C), and as late as 5 November (at a weekly mean temperature as low as 12.7°C). Again, this is a four week difference in timing and a 5.0°C difference in temperature.

Table 3. Timing of first observed spawning and mean water temperature (°C) during 7 days prior to observation for both the Upper Hells Canyon Reach of the Snake River (UHC) and the Lower Hells Canyon Reach of the Snake River (LHC).

Year	First Observed Spawning UHC	Mean Water Temp. (°C) During 7 Days Previous UHC	First Observed Spawning UHC	Mean Water Temp. (°C) During 7 Days Previous LHC
1991	11 Nov	12.5	28 Oct	13.6
1992	05 Nov	14.5	05 Nov	12.7
1993	01 Nov	14.1	25 Oct	13.9
1994	24 Oct	15.9	01 Nov	12.7
1995	23 Oct	15.0	30 Oct	11.2
1996	21 Oct	15.8	28 Oct	11.5
1997	27 Oct	13.5	20 Oct	14.1
1998	26 Oct	14.5	26 Oct	12.1
1999	18 Oct	16.1	18 Oct	15.1
2000	09 Oct	17.3	23 Oct	13.6
2001	09 Oct	19.1	09 Oct	17.9
2002	21 Oct	15.7	21 Oct	13.7
2003	20 Oct	17.5	27 Oct	14.7
2004	25 Oct	16.5	18 Oct	15.7
2005	18 Oct	16.6	18 Oct	14.9
2006	23 Oct	15.8	23 Oct	13.6

During recent years (1998-2006), spawning within the Clearwater River has tended to begin approximately two weeks earlier than in the Snake River (range between 4 to 29 days earlier; Table 4). The initiation of spawning in the Clearwater River has been observed as early as 23 September, and as late as 12 October, a difference of about three weeks in timing. From available data, it appears that when spawning occurs within the Clearwater River, the mean weekly water temperature for the seven days prior to when the first redds are observed has been between about 9.4-13.5°C.

Table 4. Timing of first observed spawning and mean water temperature (°C) during 7 days prior to observation (measured at both Lewiston and Peck) for fall Chinook salmon in the Clearwater River.

Year	First Observed Spawning CLRWTR	Mean Water Temp. (°C) During 7 Days Previous (Lewiston)	Mean Water Temp. (°C) During 7 Days Previous (Peck)
1998	12 Oct	No data	No data
1999	05 Oct	No data	No data
2000	05 Oct	No data	No data
2001	03 Oct	No data	No data
2002	01 Oct	12.3	No data
2003	23 Sep	13.5	11.6
2004	28 Sep	13.4	11.3
2005	10 Oct	No data	9.4
2006	25 Sep	13.1	11.9

During the years (1992-2006), spawning within the Grande Ronde River, has tended to begin three days earlier than in the Snake River (range between 1 day later and 14 days earlier; Table 5). The first observed spawning in the Grande Ronde River has occurred as early as 8 October to as late as 26 October, a difference of about three weeks in timing. From available data, the mean weekly water temperature for the seven days prior to when the first redds are observed within the Grande Ronde River has been between 7.6-13.3°C.

Table 5. Timing of first observed spawning and mean water temperature (°C) during 7 days prior to observation for fall Chinook salmon in the Grande Ronde River.

Year	First Observed Spawning GRonde	Mean Water Temp. (°C) During 7 Days Previous
1992	23 Oct	11.0
1993	25 Oct	9.9
1994	24 Oct	No data
1995	23 Oct	No data
1996	21 Oct	No data
1997	20 Oct	7.6
1998	26 Oct	8.6
1999	11 Oct	No data
2000	16 Oct	11.5
2001	09 Oct	12.5
2002	21 Oct	9.1
2003	08 Oct	No data
2004	12 Oct	13.3
2005	11 Oct	12.3
2006	24 Oct	9.7

Generally, the initiation of spawning in the upper Hells Canyon Reach of the Snake River occurs by about 23 October, at a mean water temperature of 15.7°C. The initiation of spawning in the lower Hells Canyon Reach of the Snake River occurs by about 24 October, at a water temperature of 13.8°C. As an additional note, during 12 of the 16 years of data, spawning began in the upper Hells Canyon Reach either before or on the same date as it did in the lower Hells Canyon Reach, when water temperatures averaged 2.5°C warmer than in the lower reach. If spawn time were solely temperature related, the question as to why fish in the lower reach do not always initiate spawning at an earlier date when water temperatures are cooler would remain. Spawning within the Grande Ronde River tends to begin by about 18 October, at a water temperature averaging 10.6°C. Also, spawning within the Clearwater has tended to begin by about 1 October, at a water temperature that averages somewhere between 11.1-13.1°C. It is further confounding that fish within the Grande Ronde River tend to begin spawning almost three weeks later than fish in the Clearwater River, but at water temperatures that are somewhere between 1-3°C cooler. It is not evident that cooler water in the Grande Ronde River leads to earlier spawning (compared with the Clearwater River).

Based on this review, it is the conclusion of IPC; that there is no evidence that spawn timing has been greatly altered in the Snake River as a result of the shift in the thermal regime by the Hells Canyon Complex. This is based on comparisons of pre-HCC spawn time distribution to that of the present-day Hells Canyon spawn time distribution. Further, spawn timing appears to be strongly associated with a declining thermal regime and likely other environmental cues that are consistent regardless of water temperature, such as photoperiod, rather than a specific water temperature.

4.6 Incubation Survival

The primary questions in this area of inquiry are how water temperature may affect the final survival of incubating embryos of Snake River fall Chinook salmon, and how temperature may influence the expression of an ocean-type life history of these fish. There appear to be many studies from which to draw inference to these questions, however many of the following factors influence the usefulness of these studies relative to these specific questions. These factors include the following four considerations.

1) Many of these studies pertain to other races or species of Pacific salmon. Fall Chinook salmon is the only Pacific salmon that spawns during the fall (October through December) within the mainstem of the Snake River downstream of the Hells Canyon Dam. As such, the spawning and incubation requirements of other salmonid species, and to some extent other Chinook salmon races, are not relevant. Generally there are small differences in thermal responses among stocks and these differences increase from races, subspecies to species and then families of fishes (McCullough et al. 2001). Genetic variation exists within Chinook salmon and other salmonids of the Pacific Northwest, as indicated in classification diagrams constructed by the National Marine Fisheries Service (McCullough et al. 2001). It is clear that based on ***constant*** temperature studies, different

species exhibit differential upper and lower threshold temperatures, relative to survival, for incubating embryos. For example sockeye salmon (13.5° C) and Chinook salmon (14.9° C) have been reported to have different upper threshold temperatures for incubating embryos (Combs and Burrows 1957, Combs 1965). ***Constant*** temperature studies of embryo survival (such as Murray and McPhail 1988) and investigations of temperature and its effect on embryonic developmental rate and emergence timing (such as Beacham and Murray 1990) have shown that the various species of anadromous Pacific salmon are **"… adapted to different spawning times and temperatures, and thus indirectly adapted to specific incubation temperatures …"**. For example, Murray and McPhail (1988) demonstrate that chum salmon and Chinook salmon have considerably greater embryo survival through emergence at warmer ***constant*** test temperatures (50% and 46%, respectively), than do other Pacific salmon species (pink salmon – 22%, coho salmon – 11%, and sockeye salmon– 8%). Finally, while Beacham and Withler (1991) showed that final mortality of ocean- and stream-type Chinook salmon juveniles, based on ***constant*** elevated water temperature, were similar, the ocean-type progeny survived for a significantly longer period of time at elevated temperatures. Those authors speculated that ocean-type Chinook salmon are better adapted to warmer water conditions.

2.) Given the best possible scenario, the most instructional data concerning incubation survival relative to thermal conditions would take into account the thermal conditions that the adults were exposed to prior to spawning, especially during the pre-spawn gamete maturation period. Several studies (presented in section 4.3 above) are often cited for confirmation of the negative effect of elevated water temperature during the adult pre-spawn period on gamete viability and ultimately embryo survival (see McCullough et al. 2001). Upon further review, it is evident that there has been very little research in this area of pre-spawn gamete viability and there is no clear conclusion as to the effect of elevated pre-spawn temperatures on gamete viability. It is apparent that the adults from which gametes were obtained for these studies were either exposed to generally cool hatchery water conditions, or their thermal history is unknown (Johnson and Brice 1953, Donaldson 1955, Olson and Foster 1955, Hinze et al. 1956, Seymour 1956, Combs and Burrows 1957, Seymour 1959, Rice 1960, Combs 1965, Jewett 1970, Olson et al. 1970, Healey 1979, Garling and Masterson 1985, Neitzel and Becker 1985, Murray and Beacham 1987, Murray and McPhail 1988, Beacham and Murray 1989, Geist et al. 2006). It is evident from many of these studies that there is significant difficulty in maintaining such large adult fish in crowded, captive conditions for extended periods of time prior to spawning. Most of the reports cited in the EPA Region 10 review to support their thermal criteria for incubating salmonid embryos faced these types of problems when including holding adult Chinook salmon (McCullough 1999, McCullough et al. 2001).

3.) Throughout the available literature concerning Chinook salmon incubation survival, it is apparent that test embryos have been maintained through several various stages, including eyed (Johnson and Brice 1953, Rice 1960), hatch (Donaldson 1955, Seymour 1956, Combs and Burrows 1957, Seymour 1959), emergence (Garling and Masterson 1985, Neitzel and Becker 1985, Murray and Beacham 1987, Murray and McPhail 1988, Beacham and Murray 1989, Geist et al. 2006), and fry feeding (Johnson and Brice 1953, Donaldson 1955, Olson and Foster 1955, Hinze et al. 1956, Hinze 1959, Jewett 1970, Jewett and Menchen 1970, Olson et al. 1970, Healey 1979). Survival through at least the emergence life stage (the end of what would constitute incubation) is more meaningful to assess the influence of water temperature through incubation.

4.) When reviewing the many studies available on how water temperature affects the survival/mortality of incubating Chinook salmon embryos (through any developmental stage), it becomes apparent that the type of thermal regime that the test organisms have been exposed to is quite variable and may not represent natural thermal regimes. Two basic types of studies (with many variants of exposures) are most prevalent in the literature: constant or variable/natural. EPA documents reviewed and reported on incubation survival and mortality data from both constant and variable thermal experiments, but seemed to rely most on constant temperature analyses to defend their regional guidance. The EPA concluded that **"As discussed previously in this paper, constant laboratory test temperatures of 48.2-50°F (9-10°C) should be considered roughly equivalent to naturally fluctuating stream temperatures with daily maximums of 51.8-53.6°F (11-12°C)"** (McCullough et al. 2001). There is only a very general, brief discussion of this conclusion and it does not appear to be sufficiently supported to justify its use. The derivation of this relationship appears to be based on growth tests of juveniles (usually rainbow trout) and not survival/mortality experiments concerned with egg incubation. More importantly, those studies that tend to indicate that constant temperature regimes were similar to fluctuating regimes stemmed from data that actually varied the test temperature cyclically around a "mean, constant" temperature rather than a declining thermal regime. The data from those experiments have little to do with a naturally declining thermal regime most commonly present in large river systems and are not properly applicable in the context of a natural regime. While constant temperature experiments have their use, mostly for determining how hatchery production can be more efficient, they are not particularly useful in defining how developing embryos might be affected in a natural habitat, such as in the Snake River. This becomes obvious if researchers were to plot the thermal exposure conditions that are normally observed within the Snake River as well as what have been used in laboratory constant exposure studies, such as Seymour (1956; Figure 10).

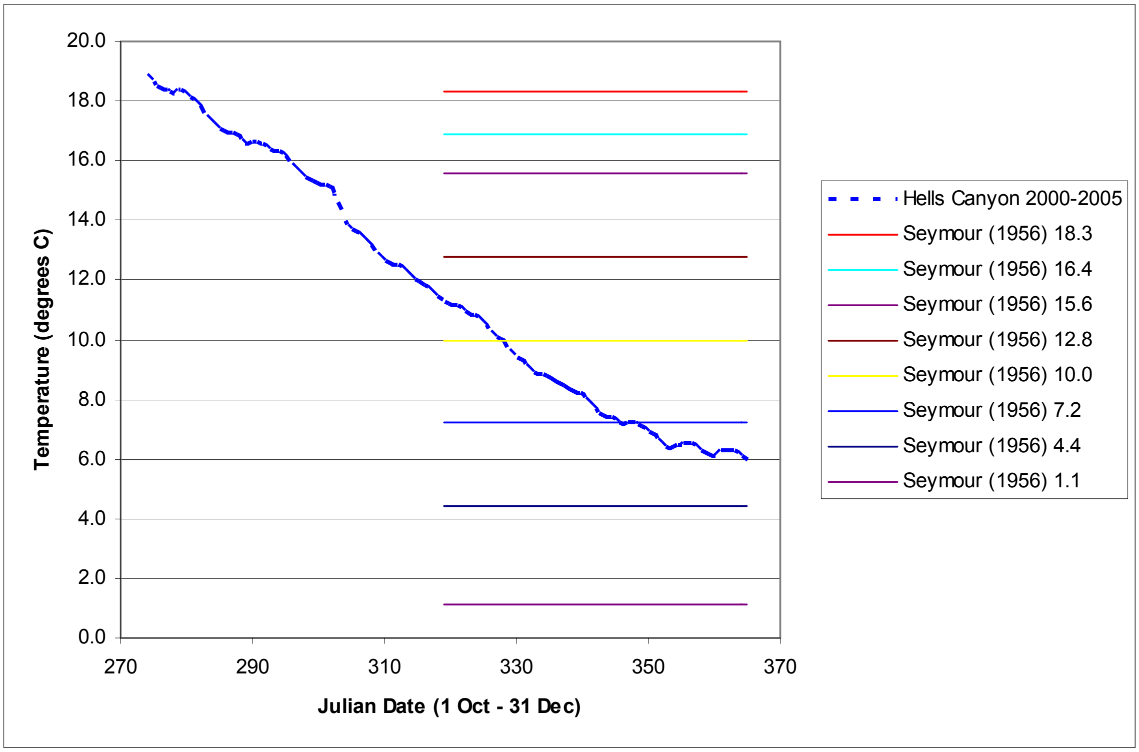

Figure 10. Comparison of maximum daily water temperature reported for the Mokelumne River (1967) and the mean daily maximum temperature in the upper Hells Canyon Reach of the Snake River (2000-2005)

However, constant temperature experiments can be useful as a basis for estimating how long incubating embryos can be maintained at specific temperatures prior to succumbing to excessive mortality. For example, by examining results from several studies (using constant and variable temperature regimes), it is evident that above about 13.0° C, the survival of Chinook salmon embryos may be negatively affected based on a function that includes how high the water temperature is, the dissolved oxygen level present, and the amount of time that the embryos are exposed to specific conditions (Healey 1979). Longer exposure to higher water temperature and lower dissolved oxygen will eventually result in increased mortality of incubating Chinook salmon embryos. Also, while conditions of warmer water temperature may not necessarily result in increased mortality, they may result in fry being smaller (both in length and weight) than individuals incubated in a cooler environment (Donaldson 1955, Heming 1982). However, there is a trade-off that occurs across the continuum of "warmer temperature – smaller fry" <u>through</u> "cooler temperature – larger fry." First of all, the difference in size, while often statistically significant, is generally quite small – often a few millimeters in length or a few milligrams of weight (Donaldson 1955, Olson and Foster 1955, Heming 1982). This is often suggested to result in a reduced survival opportunity for the smaller fry (Donaldson 1955). However, smaller fry produced from slightly warmer conditions will tend to hatch, emerge, and begin feeding earlier (Olson and Foster 1955, Heming 1982, Heming et al. 1982). This has also been suggested to provide an increased survival opportunity (Heming 1982). As well, fry that begin feeding at smaller size, but at an earlier time, will tend to grow as large, or larger, than later emerging fry, thus compensating for their smaller size at emergence (Olson and Foster 1955).

The following sections review literature often cited to support the effect of temperature on incubation success and attempt to evaluate the applicability of these studies to Snake River fall Chinook salmon based on the above four factors and then will synthesize the findings from these studies to make conclusions regarding Snake River fall Chinook salmon and incubation. Each review makes note of what stock was studied, whether notes concerning the disposition of adults were recorded, what the thermal exposure of the embryos was, to what stage of development the embryos were maintained, and the final survival/mortality data that was provided. A few of the relevant studies have previously been reviewed earlier in this paper. Those works will be noted, but will not be covered a second time.

4.6.1 Egg Incubation Temperatures

Johnson and Brice (1953)

The impetus for this study was based on depressed survival of Chinook salmon embryos at the Dorena Hatchery, in Oregon. The investigators hoped to learn whether the depressed survival was due to toxic water conditions, elevated incubation temperatures, or handling conditions. Both spring and fall stocks of Chinook salmon were tested. Experiments were conducted over the course of two incubation seasons, 1951-1952 and 1952-1953. It appears that the fall Chinook salmon used in this study originated from two sources; during 1951-1952 adults were provided from Spring Creek Hatchery, and during 1952-1953 adults came from the Little White Salmon Hatchery. The first season of testing maintained some of the test lots through emergence and into the feeding stage; however, during the second season of tests all treatment lots were terminated at the eyed stage because the hatchery was at that time permanently closed. There were no notes or observations as to what conditions the adults during each season were exposed to prior to spawning.

During the first season of testing, fertilized embryos were subjected to various treatments. Fertilized eggs from several females were mixed together and were then split into single test lots. One lot of eggs (lot A) was spawned and maintained at the originating hatchery (Spring Creek). These eggs were to be used as the control group. Two egg lots were maintained for a brief period (approximately 2.5 hours) in sealed jars and were either kept at the originating hatchery (lot B) or were driven about before being returned to the originating hatchery (lot C). Eggs from these tests were maintained through the eyed stage, and results were used to determine if handling and transportation conditions led to increased mortality. Three other egg lots were also placed in sealed containers and driven to Dorena hatchery where they were exposed to three different thermal regimes. The thermal conditions used for exposures at Dorena hatchery included the following: coolest water available at the hatchery (lot D), cool water that was chilled even further by between 2.8 to 5.5° C (lot E), and the warmest water available at the hatchery (lot F).

Unfortunately, embryos from the fall Chinook salmon were not exposed to the warmest thermal conditions.

The results from the first season of study that are most important come from lots A, D, and E. Unfortunately, no thermal data was provided for lot A; however, mortality was reported as 12.1%. Embryos in lot D began incubation at about 12.8° C, increased to a high of 15.6° C, and then declined to a low of about 7.0° C. These embryos remained at about 15.6° C for approximately 12 days. Mortality for this group was reported as 17.5%. The thermal regime for Lot E began at a temperature of 10.0° C, increased to a high of 12.8° C, and then declined to a low of about 7.0° C. Mortality for this group was reported as 9.5%. At first glance, it might be deduced that the warmer thermal regime of lot D resulted in significantly higher mortality than what was observed for the control lot A, or the coolest lot E. However, because no replicates for each thermal exposure were maintained, it was not possible to assess variability or to test for statistical differences among the various test groups. The embryos in lot D were also subjected to a warm temperature (15.6° C) for a relatively long time period (12 days). This would likely have a negative effect on embryo survival. Also, because eggs from several females were mixed together, it was impossible to assess variability due to parental lineage.

During the second season of tests, embryos were obtained from several females on 24 September and mixed together. Three lots of eggs were subjected to different thermal conditions and were maintained through the eyed stage (12 November); at that point the tests were terminated. The first group (lot A) was again spawned and maintained under conditions present at the originating hatchery (Little White Salmon). A second group (lot D) was spawned at Little White Salmon hatchery, transported to Dorena hatchery in sealed jars, and then maintained in the coolest water available at the hatchery. A third group (lot E) was spawned and transported in a similar fashion to lot D, but was maintained at Dorena hatchery under thermal conditions that were about 12.0° C cooler than the ambient environment.

Again, no thermal data was presented during the second season for egg lot A (the control group). However, mortality, through the eyed stage, was recorded as 3.7%. Egg lot D had 100% mortality through the eyed stage. However, it was noted that these embryos were exposed to a ***minimum*** temperature of 18.3° C. Egg lot E suffered a mortality of 3.6%, and it was noted that the highest temperature that these embryos were exposed to was 11.9° C. No replicates were maintained, and as such it was again impossible to assess variability and to test for differences among groups.

This early study initially had a very good overall design, and could have resulted in very insightful data concerning the effects of water temperature on incubation survival. However, because no replicates were maintained throughout any of the tests, no thermal data was presented for the control groups, and the second season was terminated early, the data are of very little use. There were no observations that can provide valuable data on variability, nor can tests for statistical differences be conducted. The results from the first season tend to indicate that water temperatures as high as 15.6° C for as long as 12 days (lot D) can result in elevated mortality; however, this is not confirmed statistically.

The authors are likely correct in their final conclusions, that high water temperature at Dorena Hatchery resulted in excessive embryo mortality at that hatchery, and that temperatures less than about 12.0° C can result in good survival of Chinook salmon embryos. It is also quite obvious that maintaining Chinook salmon embryos at temperatures above 18.0° C ***for as long as 49 days*** (lot D during the second season) will result in 100% mortality.

Finally, the thermal exposure regimes used in this study, and that resulted in the highest mortalities, are not similar or typical to what occurs within the Snake River during the spawning and incubation period of fall Chinook salmon. As with some of the studies discussed earlier concerning the effects from pre-spawn thermal conditions on embryo survival (Jewett 1970 and Jewett and Menchen 1970), the temperature of the Dorena Hatchery tests increased through early incubation before cooling. Also, test embryos tended to remain at higher temperatures for a long period of time (12 days at 15.6 ° C or 49 days at about 18.0° C). While the Dorena Hatchery temperature conditions may have been "normal" for that system, they are certainly not representative of what occurs within the Snake River historically or presently.

Donaldson (1955)

The data provided from this study were the result of two seasons of tests. The tests were designed to determine how elevated water temperature during early incubation of Chinook salmon affected survival. Adults from which gametes were collected were obtained from Green River Hatchery, Washington, a fall-run stock from nearby Soos Creek. Prior to spawning, adults were maintained at the hatchery, and held at approximately 13.6° C. During each season, groups of test embryos were maintained at various constant temperatures until attaining specific developmental stages. At the completion of each predetermined stage, test lots were transferred to an optimum, control temperature bath. During each season, the actual test temperatures were different, and ranged from 16.7 to 19.4° C. For all experiments the author intended to maintain test organisms through the feeding stage; however, complications with the water filtration system during the first season resulted in termination of the experiment just after the hatch stage, and bacterial invasion during the second season made it difficult to successfully maintain the control groups.

During the first season, after fertilization all embryos were mixed. Embryos were initially maintained at three test temperatures (16.7, 18.3, and 19.4° C), and a control temperature (11.8° C). Each temperature treatment contained five test lots of 250 eggs each. One lot within each treatment temperature was kept at the initial test temperature throughout the experiment. The four other test lots within each treatment were maintained to a specific developmental stage (100, 200, 350, and 500 Fahrenheit thermal units) before being transferred to the control temperature. Final mortality and abnormalities were noted for each test lot. This design prevented replication of test results within each of the test temperatures, limiting statistical comparisons among treatments.

The first season's tests were complicated due to water filter failures. Because of this, the tests were concluded early, just post-hatch. The results from the first season were not particularly useful, but did indicate that mortality at exposure temperatures ≥18.3° C were greater than what was observed for the lower test temperature (16.7° C) or for the control groups.

During the second season, embryos from two females were used, and were kept separate in order to evaluate responses due to parental lineage. The basic design of the experiment was similar to that of the first season, except that the lower test temperature of 16.7° C was increased to 17.2° C, and the control temperature was maintained at approximately 12.8° C. Finally, the test embryos were able to be kept through the initial feeding stage. While filtration complications were eliminated during the second season, severe bacterial growth made it difficult to successfully maintain the control lots.

Eggs from female two had much higher mortality within each temperature treatment, including the control. For example, total mortality, through feeding, for eggs from female one was about 20%, while for female two it was 99%. Within all treatments, the shortest exposure time did not result in elevated mortalities during the pre-hatch period. However, as exposure time within each treatment was increased, total mortalities also increased. As well, it was noted that while warmer exposure temperatures resulted in faster development, the resultant fry tended to be smaller than control cohorts. Finally, the data tended to point out that mortality was higher within all groups (test and control) during specific developmental stages (during the hatch period, and during the transition from final yolk absorption to active feeding).

The tests for this study were designed to result in increased mortalities; this is an important note to keep in mind. While this study does provide some useful information, again, it was impossible to statistically analyze the data as only one lot of eggs was exposed to specific treatments. For example, while there were five lots within any one temperature treatment, each lot was exposed over a different amount of time, thus no replicates were available for each treatment. The most useful information that can be derived from this work is that mortality can be elevated (even under the most optimum thermal conditions) during specific developmental phases. Also, it is noteworthy that developmental rates can be accelerated at warmer temperatures, and that embryos that have been exposed to warmer temperatures can be smaller than cohorts exposed to cooler conditions.

Olson and Foster (1955)

This experiment was undertaken due to a concern that warming of the water during early incubation of Chinook salmon embryos in the Columbia River, due to heated power plant effluent, might result in elevated mortalities. Data were collected through a single season of incubation. Gametes for the test were collected from a fall-run Chinook stock of the middle Columbia River (Hanford Reach). Adults were collected from the river and spawned in the field on 26 October. Unfortunately, adult pre-spawn exposure temperatures are unknown. However, recent data for that reach indicates that from 1

October through 26 October water temperatures tend to decline, and to range from 17.9 to 14.8° C (mean of data from the Columbia River DART web page, 1995-2006). After initial spawning, test embryos were placed and maintained within five different temperature treatment groups. While each treatment temperature was different, they all followed a declining, then increasing regime pattern that is seasonally typical for that river. The five temperature treatments began at 11.6, 13.8, 15.0, 16.1, and 18.4° C. These initial test temperatures were also the highest temperatures that embryos were exposed to during their development. The temperature treatment that began at 13.8° C was noted as following a thermal regime that was typical for the river reach in question. Embryos were maintained well into the fry feeding stage. After feeding began, samples from each treatment were removed and weighed on a two-week interval. Final mortalities were noted.

Olson and Foster (1955) were able to conduct some level of statistical analysis. The authors conclude that only in the highest test temperature of Lot E was mortality among eggs, fry, and fingerlings significantly greater (at the 5% level of probability) than what was observed in the control Lot B. Additionally, as will be shown later, the data from this study can be combined with that of a later test using the same fall-run Chinook stock and similar thermal treatment conditions (Olson et al. 1970), as well as results from Geist et al. (2006). By combining those data, one can assess variability and accomplish, and enhance the clarity of, statistical tests to determine significant differences.

This experiment was certainly a more realistic attempt to describe how elevated water temperature may affect the survival or mortality of incubating fall Chinook salmon embryos exposed to a natural thermal pattern. Adults were collected and spawned in the field, and as such were exposed to natural thermal conditions present in the Hanford Reach of the Columbia River just prior to spawning. Each temperature treatment exposure was different, and they all followed a natural thermal pattern. The final mortality data was statistically evaluated indicating that mortality was similar at initial temperatures between 11.6 and 16.1° C (range of 7.8 to 16.1%), but highly elevated (79.0%) at an initial temperature of 18.4° C (Table 6). Also, data from this experiment validated that warmer temperature during incubation led to faster development and earlier emergence and slightly smaller fry upon emergence. However, the fry that emerged earlier and smaller began feeding earlier and grew faster than later emerging, larger cohorts.

Table 6. Final mortality data (through feeding stage) for incubating Hanford Reach fall Chinook salmon as a result of initial exposure temperature.

Initial Exposure Temperature (° C)	Final Mortality (%)
11.6	7.8
13.8	16.1
15.0	10.1
16.1	10.4
18.4	79.0

Hinze et al. (1956)

This report was previously reviewed in the section concerning adult pre-spawn conditions.

Seymour (1956)

This work was undertaken in order to determine how temperature affects development rate, as well as how temperature might induce “abnormalities”. A series of three experiments were conducted over three incubation seasons. Several different stocks of Chinook were used. During the first two seasons of study, gametes were obtained from Green River fall Chinook salmon. During the third season of study, four different Chinook stocks were used: Skagit River (spring Chinook), Entiat River (fall Chinook), Sacramento River (fall Chinook), and Green River (fall Chinook). The environment that adults were exposed to prior to spawning was not reported. The temperature treatments that embryos were exposed to during the first two seasons were constant, whereas the exposure treatments of the third season followed a more natural, seasonal thermal pattern, declining through the winter and increasing through the spring. The survival data are somewhat sketchy, and while it is not directly stated in the text of the work, it is evident that these data are only presented through the hatch stage.

During the first season embryos were maintained at eight different constant thermal conditions (1.1, 4.4, 7.2, 10.0, 12.8, 15.6, 16.9, and 18.3° C). During the second season, embryos were maintained at seven different constant thermal conditions (7.2, 10.0, 12.8, 14.7, 15.6, 16.9, 18.3, and 19.7° C). The results from the first two seasons indicated that mortality through the hatch stage was low and similar (≤10%) for all egg lots incubated at constant temperatures less than 15.6° C. Embryo groups incubated at constant temperatures of 15.6° C and higher had significantly greater mortality. It should be noted that during the second season of this study, a filter problem occurred, and substantial mortality occurred throughout all test groups. Also, while few actual numbers were recorded, the following information was reported:

1. Eggs incubated at constant temperatures of 1.1 and ≥18.3° C had 100% mortality.
2. Eggs incubated at constant temperatures 15.6 and 16.9° C had high mortality prior to hatching, and then total mortality during the yolk absorption period.
3. Eggs incubated at constant temperatures of 12.8 and 14.2° C had low mortality prior to hatching, and then high mortality during the yolk absorption period.
4. Eggs incubated at constant temperatures of 4.4, 7.2, and 10.0° C had low mortality throughout all developmental stages.

During the third season, initial test treatments began at the following temperatures: 7.2, 10.0, 12.8, 15.6, and 18.3° C. Each treatment group had the temperature reduced by 0.5° C every five days until they reached 1.1° C. Each treatment group was then maintained at this low temperature for 20 days, at which time the temperature was then increased by 0.5° C every five days. One lot of eggs was kept as a control and was maintained at a constant 12.2° C throughout the third season of tests. The author reported low mortality (generally less than 5%) through the hatch period for all treatment groups incubated under a "natural" thermal regime when initial temperature was ≤15.6° C. The author also noted that test groups that resulted in high mortality through the hatch stage were exposed to temperatures ≥17.0° C for at least 15 days.

This very involved study was not specifically designed to provide data on incubation mortality or survival, and as such it does not provide very useful data on that subject. However, a few noteworthy observations and conclusions were made based on the results from the three seasons of work. The first was that survival/mortality results (at least through the hatch stage) were different based on whether the embryos were subjected to constant or "naturally variable" temperature conditions. If embryos initially began incubation under the same elevated temperature as high as 15.6° C, those kept under constant conditions suffered high mortality through the hatch stage, while those that experienced a more normal thermal regime had very low mortality through the hatch stage. This information is very important, as it indicates that survival/mortality data based on constant temperature studies may not represent what occurs in a naturally variable environment. A second observation stemmed from a few of the control egg groups being accidentally maintained at very low dissolved oxygen (≤3.0 mg/L) levels for 21 days. Those embryos suffered very low mortality (less than 10%), indicating that low dissolved oxygen during early incubation (prior to hatching) does not result in increased mortality. Finally, it was observed that under constant thermal conditions, high and low temperatures resulted in increased abnormalities (increased number of vertebrae), while embryos subjected to a natural thermal regime did not suffer from increased abnormalities, even when the initial exposure temperature was elevated. All of these observations indicate that exposing Chinook salmon embryos to constant thermal conditions during incubation produces very different results compared to exposure to more natural, variable thermal conditions.

Combs and Burrows (1957)

These authors reported on a series of constant temperature tests that were conducted over a period of three years. These experiments were conducted to determine more efficient methods for managing hatchery environs. Eggs were obtained from Entiat and Skagit River Chinook stocks; however, it was not stated whether these were spring, summer, or fall-run stocks. No records were provided as to the thermal conditions that the adults were exposed to prior to spawning. Embryos were maintained at several constant temperatures, including: 1.7, 3.1, 4.4, 5.8, 7.2, 10.0, 12.8, 14.2, and 15.6° C. Embryos were only maintained through the hatch stage.

The authors observed that at a constant temperature of 1.7° C 100% mortality occurred. Based on their results, they estimated that the lower threshold temperature was 5.1° C, and that the upper threshold temperature was 14.9° C. They also noted that as long as early incubation temperatures were above 4.4° C, then embryos could successfully tolerate colder temperatures during later stages of incubation. Finally, the authors wanted to make certain that future researchers understood that the results from this work were only valid for describing development under constant temperature conditions; they noted:

“The range of incubating temperatures between 42.5 and 57.5 degrees F, established by these experiments as the range for normal development, applies only to constant temperatures”.

Hinze (1959)
This report was previously reviewed in the section concerning adult pre-spawn conditions.

Seymour (1959)

This paper is derived from data previously reported in Seymour (1956), and as such provides no additional information.

Rice (1960)

This report was previously reviewed in the section concerning adult pre-spawn conditions.

Combs (1965)

This paper reports on the effects of constant temperatures on the survival/mortality of incubating sockeye and Chinook salmon embryos. The tests conducted were mostly done on sockeye embryos, but a connection was made to earlier work done on Chinook salmon by Combs and Burrows (1957). The thermal conditions to which adults were exposed to prior to spawning were not described, nor was it specifically stated to what stage the embryos were maintained.

The author determined that the lower threshold temperature of sockeye salmon was approximately 5.1° C, and that the upper threshold temperature was 13.5° C. It was concluded that, citing results from Combs and Burrows (1957), sockeye were more tolerant of colder temperatures and less tolerant of warmer temperatures when compared to Chinook salmon. This is an important point, indicating that different salmon species have different thermal tolerances. Also, the author reiterated that the results from these experiments were based on constant temperature, and should not be used to estimate what might occur in a natural environment: **“We emphasize that the results of the threshold temperature experiments were derived from constant incubating temperatures. The conditions imposed upon the sockeye salmon eggs in these tests would rarely be duplicated in nature or in artificial propagation procedures”**.

Jewett (1970)

This report was previously reviewed in the section concerning adult pre-spawn conditions.

Jewett and Menchen (1970)

This report was previously reviewed in the section concerning adult pre-spawn conditions.

Olson et al. (1970)

This study was a later expansion on what was previously done by Olson and Foster (1955), and is a more detailed description of the methods and results that were reported on by Olson and Nakatani (1968). The experimental procedure was designed to test how elevated water temperatures during early incubation development might affect final survival/mortality of Chinook salmon embryos. The Chinook stock used for this study was the fall-run stock of the Hanford Reach of the Columbia River. Adult salmon were spawned at the Priest Rapids hatchery; however, no data is reported as to the thermal conditions that adults were exposed to prior to spawning. Gametes were collected from single female/male pairs at four times during the spawning season: 30 October, 14 November, 23 November, and 8 December. At the time of spawning, groups of embryos were randomly placed in one of seven thermal environments. One of the embryo groups was always placed into conditions that mimicked natural Columbia River water temperatures. The other groups included conditions that were 2.0, 4.0, and 6.0° F warmer than ambient river conditions, and 2.0, 4.0, and 6.0° F cooler than ambient river conditions. Dissolved oxygen was maintained near saturation. Test organisms were maintained into the fry feeding stage.

The resulting data indicated several interesting points. Later spawned eggs, from adults acclimated to cooler conditions, were able to tolerate a larger thermal increment away from the normal river temperature. Very warm conditions during early incubation generally resulted in increased mortality. These authors noted that delayed mortality, resulting from early exposure to high temperature, tended to occur in later developmental stages. The most critical period where delayed mortality tended to occur was during the shift from yolk absorption to active feeding. Increased temperature tended to accelerate development and growth of embryos. In contrast to other study results, this work indicated that, at the same accumulated thermal units, embryos exposed to warmer temperatures tended to be heavier than their cohorts exposed to cooler temperatures. Finally, the authors concluded that, given a naturally variable thermal regime, increased mortality tended to occur when initial water temperature during incubation was above about 16.0° C. However, a closer examination of the data from this study indicates that the initial exposure temperatures were not the highest that embryos were subjected to. Based on the data provided, it appears that increased mortality actually resulted at temperatures that at some point during early incubation exceeded 16.5° C. As with Olson and Foster (1955), the results from this study are more relevant to how water temperature affects Chinook salmon embryo survival than are any constant temperature experiments.

As with most all other earlier experiments, no replicates were maintained for any single exposure temperature. Therefore, variance could not be estimated, nor could statistical tests for differences be conducted. However, the data from this experiment can be combined with information from Olson and Foster (1955), as well as Geist et al. (2006), to provide a very clear description of how, given a naturally variable thermal regime, elevated water temperature during early incubation may affect Chinook salmon embryo survival. This analysis, which shows increased mortality of incubating fall Chinook salmon generally occuring at water temperatures > 16.5° C, will follow shortly (section 4.6.2).

Healey (1979)

This is another study conducted on Chinook salmon embryos designed to aid managers in determining how increased water temperature during early incubation may affect final survival of fry. The fish used for this study were from a fall-run stock of the Sacramento River, California. Tests were conducted at Coleman Hatchery near Anderson, California. There was no description as to the disposition of adults prior to obtaining fertilized gametes. The actual experiment was designed to test for egg and fry survival after exposure to various thermal regimes. Eggs were obtained on three different dates; 24 September, 22 October, and 9 November. After fertilization, eggs were mixed and roughly equal groups were maintained in three different thermal regimes; cold, cool, and warm conditions. Mortalities were recorded through at least the early stage of fry feeding.

The results from this study should be examined very carefully. Each group of eggs maintained in the warm conditions had final mortalities ≥80%. This is not surprising, as all of these eggs were exposed to fairly constant water temperatures of 15.6 to 16.1° C from 31 October through 31 December, a period of approximately 60 days. The only other group of eggs to suffer excessive, elevated mortality was the 24 September group placed in the cool water treatment. This group had a final mortality of 31%; however, they were exposed to a constant water temperature of 15.6° C for 15 days. The next highest mortality was from the 24 September egg group that was placed in the cold water treatment. These eggs had a final mortality of 13%, and had been initially exposed to a water temperature of 15.6° C for 5 days. Unfortunately, as with all other studies, no replicates were maintained within any temperature treatment. Therefore, there was no possibility to test for statistical differences due to treatments. However, the data from the spawning of 24 September strongly suggest that final mortality is not so much due to the actual thermal exposure, but more to the length of time that embryos are exposed to an elevated water temperature (Figure 11).

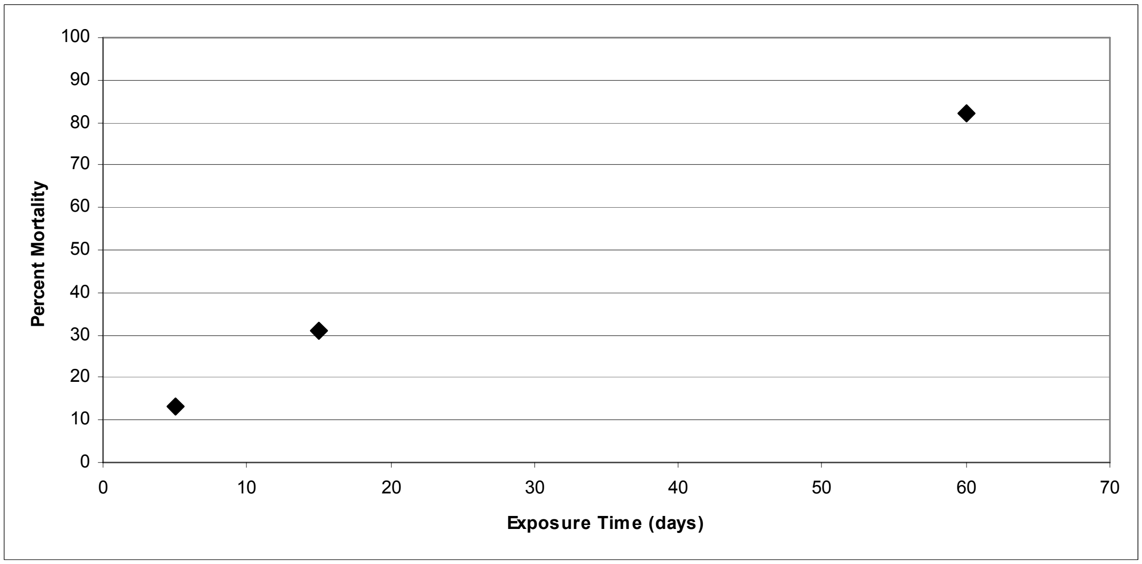

Figure 11. Percent mortality of Chinook salmon embryos dependant on exposure time (days) to water temperature of approximately 15.6 degrees C (data from Healey 1979).

While the thermal environment that embryos were exposed to in each of the three treatments were supposed to resemble a more normal, natural thermal regime, it is quite obvious that this was not the case. As mentioned above, embryos that were placed in the warm environment were exposed to water temperatures ≥15.6° C for approximately 60 days; this kind of exposure has never been observed in the Snake River. Also, early spawned embryos placed in the cool water treatment were exposed to water temperatures ≥15.6° C for approximately 15 days; again, this type of regime has never been observed in the Snake River.

<u>Heming (1982)</u>

This paper is sometimes used as a reference to support the proposition that elevated water temperature during incubation of Chinook salmon embryos results in increased mortality. However, the actual design of this study was to investigate how temperature during incubation might affect yolk conversion efficiency. The main aim of this work was to assist in developing methods that would make hatchery operations more streamlined and efficient. The stock used in the experiment was a fall-run Chinook from the Campbell River, British Columbia. There was no description as to the thermal environment that adults were exposed to prior to spawning. Fertilized eggs were maintained within four different constant temperature treatments (6.0, 8.0, 10.0, and 12.0° C). Four replicates were kept in each temperature treatment. Density of embryos was reduced at the time each group reached the eyed stage. After the hatch stage, a further reduced number of alevins from each temperature group were maintained in “artificial” redds in the lab; however, no replicates were kept during this later post-hatch developmental stage. Dissolved oxygen was maintained near saturation throughout the experiment. During the pre-hatch period, the water velocity through the incubation trays was roughly 790 cm/H.

The embryos that were placed in the "artificial" redds experienced intergravel water velocities estimated to be about 240 cm/H. Embryos were maintained through the emergence stage, but not into the fry feeding stage.

There was no specific data collected as to survival or mortality of incubating embryos. The author simply noted that survival to hatch and to emergence decreased slightly at the higher rearing temperature (constant 12.0° C); however, there was no statistical analysis performed to substantiate this observation. The development rate was increased at warmer temperatures, and emergence occurred earlier at warmer temperature. Emergence was noted to correspond with the time when maximum tissue weight was attained. It was observed that the maximum tissue weight was attained at the same development stage for all treatments; however, embryos from the warmer treatments tended to be both slightly less massive and shorter than cohorts exposed to cooler temperature treatments. It was also observed that embryos in the warmer treatments, while smaller than cohorts from cooler treatments, hatched, emerged, and began feeding earlier. The author concluded that this might actually provide territorial and survival advantages to the earlier emerging fish.

Garling and Masterson (1985)

This was another study conducted in order to help managers design more efficient hatchery operations. The question that was addressed was how maintaining Chinook salmon embryos under conditions of constant temperature might affect survival/mortality. Fish used for this study were an unknown origin Pacific Northwest fall-run stock transplanted to Lake Michigan. Constant temperature treatments included 9.9, 11.4, and 15.1° C. On a single date (13 October) 16 females were spawned, and their eggs were kept separate. Eggs were distributed so that several replicates from each female were placed into each temperature treatment. Test organisms were maintained through the emergence stage. Total survival/mortality data was not reported. Instead, survival was first recorded for all groups through the hatch period, and then a separate survival/mortality percentage was reported through emergence based on the number of living organisms present after hatch was completed.

Data from this experiment further supported that developmental rate was accelerated at warmer temperatures; hatch and emergence occurred earlier at warmer temperatures. Unfortunately, this study had several problems occur that make it difficult to assess the utility of the data. It was noted that a pump failure resulted in confounding survival/mortality data for the groups maintained at 15.1° C. It was also noted that eggs from two females had particularly high mortality within all temperature treatments; this was suggested to have occurred due to the gametes from those fish being singularly infertile. Finally, it was noted that pre-hatch survival was generally low (≤50%, with high variability) throughout all treatments; this was thought to have occurred due to poor handling procedures during early incubation. The manner in which the survival/mortality data were obtained and reported makes it difficult to make good use of the information presented in this report. However, it appears that mortality through hatch was similar in the two lower temperature treatments (9.9 and 11.4° C), and significantly higher in the highest temperature treatment (15.1° C). Finally, it should be reiterated that the results from this study are based on a constant temperature exposure treatment, something that does not occur naturally, especially in the Snake River.

Neitzel and Becker (1985)

This study was conducted to determine how short periods of warm and cold thermal shock, as well as levels of humidity, may affect incubation survival of Chinook salmon embryos. Of importance relative to this review are the results from the heat shock tests that were conducted. Gametes for this test were obtained from the Washington Department of Fisheries hatchery at Klickitat, Washington. There was no description as to the adult pre-spawn thermal conditions. Except for the periods of time when embryos were subjected to heat shock, developing embryos were maintained at a constant temperature of 10.0° C; test organisms were also maintained through the emergence stage. At specific developmental stages (60, 340, 570, and 810 accumulated Celsius thermal units – CTU), groups of embryos were subjected to different elevated temperatures (22.0, 23.5, 25.0, 26.5, and 28.0° C) for varying amounts of time (1, 2, 4, or 8 hour periods).

The tolerance of Chinook embryos to adverse conditions was noted to vary with magnitude and duration of exposure. Tolerance to shock did not appear to vary among progeny from different females. At temperatures as high as 22.0° C few mortalities were observed. Cleavage eggs (≈60 CTU) exposed to 22.0° C for as long as eight hours suffered relatively little mortality through emergence. However, for all exposure times at temperatures ≥23.5° C cleavage eggs suffered significant mortality. Embryos (≈340 CTU) could withstand exposure to temperatures as high as 25.0° C for all time treatments without suffering excessive mortality through emergence. However, for all exposure times at temperatures ≥26.5° C embryos suffered significant mortality. For all time treatments, eleutheroembryos (≈570 CTU) were observed to tolerate temperatures as high as 22.0° C with virtually no mortality occurring through emergence. At higher temperatures, and for all time treatments, eleutheroembryos suffered very high mortality. Exposure tests for pre-emergent alevins (≈810 CTU) produced results that were basically identical to those for eleutheroembryos.

Murray and Beacham (1987)

The variations of thermal conditions that embryos were exposed to during this study are somewhat arbitrary, and make very little sense; they do not represent what occurs in either a hatchery or in a natural river environment. The fish used for this study originated from the Harrison River, British Columbia; there is no direct note as to whether they were a spring, summer, or fall-run stock. However, based of the date of gamete collection (25 October), it is likely that these fish were a fall-run stock. All embryos were initially maintained at 8.0° C. After fertilization, groups of embryos were placed in constant temperature treatments of 4.0, 8.0, or 12.0° C. Control groups remained in their respective constant temperature treatments throughout the experiment. At some point during development, embryos from each group were transferred into one of the other two temperature treatments. For example, one group of eggs, initially placed in a bath of 4.0° C, would be later transferred to a bath of 8.0° C, while another group initially held at 12.0° C might be transferred to a treatment of 4.0° C. All test organisms were kept through the emergence stage.

The warmer the conditions that embryos were exposed to, the earlier they reached the emergence stage. This continues to corroborate earlier studies that reported similar observations, as well as results from Geist et al. (2006). For all Chinook embryos, survival was relatively good, always greater than 70%. Embryos that were transferred from warmer to cooler treatments tended to have higher overall survival through emergence (≥90%) than did all embryo groups started at the coldest treatment (between 70-90%). It was also noted that embryos that were initially exposed to the warmest treatment and then transferred to a cooler treatment were longer and heavier at emergence than were cohorts from other treatment exposures. These data tend to indicate that a natural thermal regime, falling through winter and then rising into spring, results in more robust fry than might constant thermal exposure throughout incubation.

Murray and McPhail (1988)

In this study, the thermal environment that embryos were exposed to was constant; it did not follow a normal, variable regime. This study actually focused on all five species of Pacific salmon: sockeye salmon, pink salmon, chum salmon, coho salmon, and Chinook salmon. The questions being investigated were how various constant thermal exposures affected survival through emergence, as well as timing of development, and size and weight of fry at emergence. The Chinook salmon used in this study originated from the Babine River, British Columbia. Embryos were fertilized at a temperature of 14.0° C. Embryos from each of the salmon species were maintained in the following constant temperature conditions: 2.0, 5.0, 8.0, 11.0, and 14.0° C. Water velocity through the incubation troughs was estimated to be 534 cm/H, and dissolved oxygen was kept at ≥85% saturation. Embryos of each species were maintained through the emergence stage.

For all species, it was reported that time to both hatch and emergence was inversely related to water temperature. Warmer test temperatures accelerated development and resulted in earlier hatch and emergence. For Chinook embryos, mortality from fertilization through emergence was very high at a constant incubation temperature of 2.0° C (86%), fairly low at constant temperatures of 5.0, 8.0 and 11.0° C (range of 10-17%), and moderate at a constant temperature of 14.0° C (54%). The data collected on the size and weight of individual Chinook fry at the time of emergence showed that fish incubated at a constant 5.0° C were longer and heavier than fish incubated at the other test temperatures (Figures 12 and 13). However, it should be noted that a constant incubation temperature of 5.0° C (or any temperature for that matter) does not occur in nature where Chinook salmon embryos incubate.

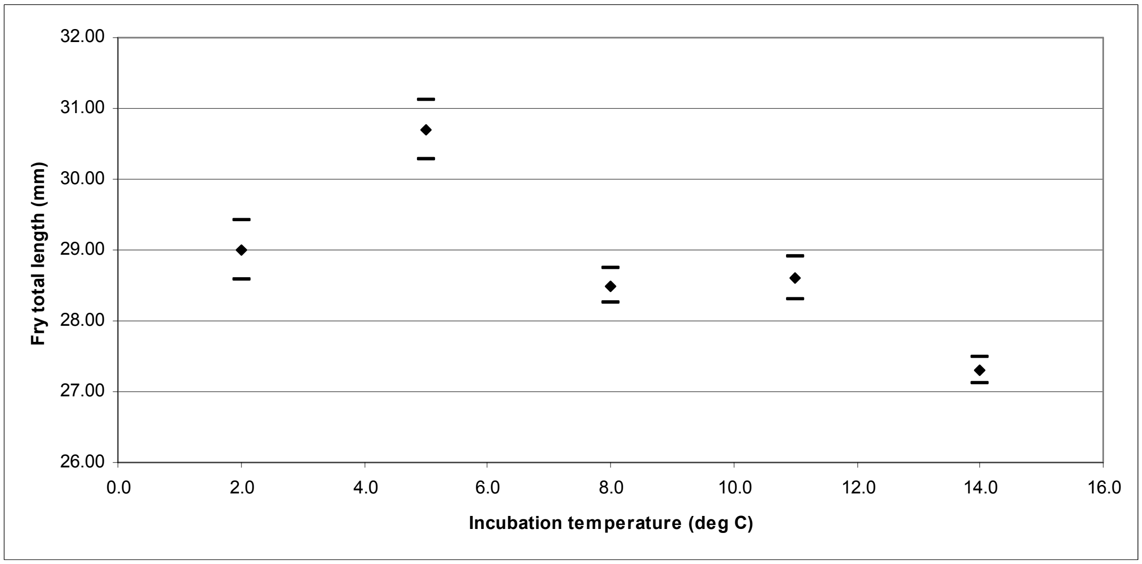

Figure 12. Mean length (and 95% confidence interval) for emergent Chinook salmon fry after incubation at various constant temperatures (data from Murray and McPhail 1988).

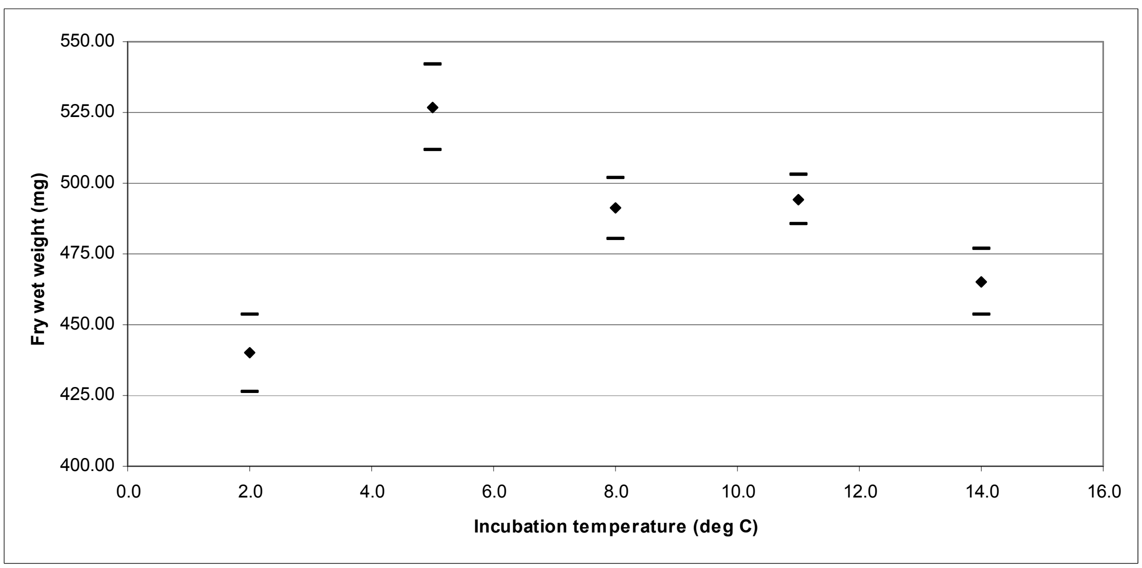

Figure 13. Mean weight (and 95% confidence interval) for emergent Chinook salmon fry after incubation at various constant temperatures (data from Murray and McPhail 1988).

The most informative results from this study concerns the differences observed among the five different Pacific salmon species. For example, at the highest treatment temperature (14.0° C) it was observed that chum and Chinook salmon had the lowest mortality, 50% and 54%, respectively, while the other three species had mortalities that ranged between 78 and 92%. Sockeye salmon were noted as being the species least able to tolerate warmer water temperature. The authors concluded, “Each species is adapted to different spawning times and temperatures, and thus indirectly adapted to specific incubation temperatures". Subjecting developing embryos to constant thermal conditions throughout incubation does very little to help us to learn how specific, naturally variable thermal regimes may result in embryo survival; however, as the data from this study illustrate, these types of constant temperature tests can help us to discern different thermal tolerances among similar species.

Beacham and Murray (1989)

The tests conducted in this study were done to assess differences in incubation development and survival, based on water temperature, between both Chinook salmon and sockeye salmon, as well as between two distinct stocks of Chinook salmon. The Chinook stocks used in this study originated from the Fraser River system, British Columbia. The two distinct Chinook salmon stocks that were compared came from a coastal and an inland run, and while it was not specifically stated, it appeared that they were both a spring-run stock. The thermal conditions that adults may have been exposed to prior to spawning were not described. All embryos were exposed to one of five constant temperature treatments (2.0, 4.0, 8.0, 12.0, and 15.0° C). Test organisms were maintained through the emergence stage.

As with other studies, this one corroborated that warmer temperature during incubation resulted in accelerated embryo development, and that emergence occurred earlier for those embryos exposed to warmer conditions. This was true for both Chinook salmon and sockeye salmon. Again it was observed that Chinook salmon tended to have better survival at warmer temperatures, and that sockeye salmon appeared to be better adapted to cooler temperatures. Finally, there was little evidence that differences in thermal adaptation existed between the two Chinook stocks. However, the authors continually brought up in their discussion the supposition that local stocks are adapted to local thermal conditions.

Beacham and Murray (1990)

This paper is quite involved and provides some very good information concerning Pacific salmon incubation in relation to water temperature. However, it should be noted that all of the data used in the development of this work were based on constant temperature exposure of test organisms. The point that constant temperature conditions are not representative of what occurs in the natural environment cannot be stressed enough. As well, the authors acknowledge that the information provided was mainly for the accurate prediction of hatching and emergence timing, and was of practical interest for managers involved in salmon culture (hatchery environs). The basic design of this work was to subject embryos of all five common Pacific salmon species to various constant temperature regimes in order to determine the upper and lower temperature at which 50% mortality occurred, to determine if differences existed in the size and weight of fry exposed to different thermal treatments, and to develop and compare various models useful in estimating the timing to hatch and emergence.

The authors were able to determine that for Chinook fry, a constant temperature of 2.0° C resulted in 50% mortality through emergence; however, they were not able to determine (based on the data used) what upper temperature resulted in 50% mortality through emergence. As with other studies, it was reported that fry resulting from warmer, constant temperature exposures tended to be smaller and weigh less than cohorts that had been exposed to cooler temperatures. Finally, while there were slight differences in how the various developmental models described timing through hatch and emergence, all of them had very low sums of squares and r-square values ≥0.99. It was determined that none of the mathematical models were any better or worse at describing developmental timing.

In the end, the authors acknowledged that all of their results were based on data from constant temperature treatments, and did not reflect what would be expected to occur in the natural habitat. The authors also noted that the data provided insight as to the variation among Pacific salmon with respect to how water temperature affected embryonic development rate, survival, and fry size and weight. A very telling quote from the conclusions was, **"Because the species showed different trends in emergence timing with respect to changes in development temperature, it seems reasonable to infer that these different trends reflect adaptive variation in the species' response to environmental temperature during development"**. And finally, the authors noted, **"Population-specific differences in development can also exist, and populations that spawn in extreme environments can probably be expected to have different rates of development and survival than populations in more moderate environments"**. This paper establishes a very good base for understanding that not only are there species-specific differences in how Pacific salmon are differentially adapted to various thermal environments, but also how population-specific adaptations are likely.

<u>Geist et al. (2006)</u>

This paper centers on how elevated water temperature coupled with low dissolved oxygen during early incubation might affect development and survival of Chinook salmon embryos. The fish used for this work originated from the Snake River, and were a fall-run stock of Chinook salmon. Prior to obtaining gametes, adults were held at the Lyons Ferry Hatchery, and were exposed to a fairly constant temperature of 12.0° C. After gametes were fertilized, they were subjected to one of 14 different temperature-dissolved oxygen treatments. Six replicates were maintained within each treatment, and as such statistical analysis was able to be conducted on the results. Test organisms were maintained through the emergence stage. Survival data was collected at various stages of development, including eye-up, hatch, and emergence.

The various treatments included five initial temperatures of 13.0, 15.0, 16.0, 16.5, and 17.0° C, coupled with four initial dissolved oxygen levels of 4.0, 6.0, 8.0 mg/L or 100% saturation. Test organisms in the temperature groups of 13.0 and 17.0° C were only exposed to 100% saturation of dissolved oxygen. Each temperature group had a declining thermal regime equal to 0.2° C per day through the first 40 days of the tests. After day 40, all treatments were thereafter exposed to a normal Snake River temperature regime as described by the mean daily water temperature of the upper Hells Canyon Reach among the years 1991-2003. As well, initial dissolved oxygen levels were maintained through the first 16 days, whereupon they were then increased by 2.0 mg/L. On day 39 they were again increased by 2.0 mg/L, and after day 40 they were maintained at 100% saturation.

Among the several studies available to date, Geist et al. (2006) is one that tests results based on using replicates within each treatment (allowing for statistical analyses), as well as exposing embryos to several different naturally varying thermal-dissolved oxygen regimes. The authors reported that survival of developing embryos was linked only to temperature. The only group that was statistically different was the one initially exposed to 17.0° C; all other groups were similar and had mean survivals ≥83% (see Table 2 in Geist et al. 2006). These results comport well with other studies that subjected embryos to thermal regimes resembling what occur in natural systems.

The authors reported that development timing was accelerated at higher temperature, and at higher dissolved oxygen levels (see Table 3 in Geist et al. 2006). Again, this information comports well with what other, earlier researchers have reported.

Lower dissolved oxygen tended to result in an increase in abnormalities. Groups initially held at 4.0 mg/L dissolved oxygen generally had twice as many abnormalities as groups started at higher levels; however, this was still a very small proportion of any group (≤6.0%), and there was no statistical difference among groups.

Finally, the growth of embryos was only very slightly affected by differences in temperature and dissolved oxygen. The wet weight at hatch, as well as the wet weight and fork length at emergence were statistically similar among all groups. While the fork length of alevins at hatch differed among treatments, the largest difference was only 1.0 mm; it is difficult to infer that this difference would have a profound effect on later survival, especially since at emergence this difference no longer existed. The most important difference that was observed, with respect to growth, was that yolk conversion efficiency tended to be better in embryos initially exposed to higher dissolved oxygen levels. At emergence, the dry weight of fry was not different among treatment groups; however, the amount of yolk was significantly less in groups that were initially exposed to 100% saturation of dissolved oxygen.

The authors did note that adults used in their tests were not exposed to normal river temperatures prior to spawning. Adults were maintained in water having a constant temperature of 12.0° C, and the authors note that this might have an undetermined effect on the final results of their experiment. Unfortunately, they correctly noted that there are no studies that have, as yet, successfully maintained adult Chinook salmon at elevated water temperature prior to spawning.

One potential criticism of this study (and other incubation studies) is that flow rates past the developing embryos in the laboratory may not have been representative of what actually occurs in the natural hyporheic environment of a redd. The authors noted that during their experiment the flow rate through the advanced post-hatch stage was maintained at about 0.18 cm/s. There is only one other study involving Chinook salmon that reported on flow rate, and that was Heming (1982); in that study, the flow rate was maintained at 0.22 cm/s. Recent research with the use of artificial redds in the Snake River in Hells Canyon estimated inter-redd horizontal water velocities during the incubation period to range from a mean of 0.14 cm/s to 1.06 cm/s at the various artificial redd sites with an overall mean among all artificial redd sites of 0.55 cm/s (Hanrahan et al. 2007). During the latter portion of the incubation period, the horizontal velocity component through the artificial redds leveled to a median value of 0.21 cm/s. These finding suggest that the laboratory studies of Geist et al. (2006) closely represent velocity conditions observed in the natural environment.

4.6.2 Synthesis of incubation survival evaluations

In summary, based on the above literature review, several consistent findings emerge regarding temperature and incubation. First, and most important, experiments based on constant and naturally varying thermal regimes provide very different results with respect to both ultimate survival and size of fry at emergence. Certainly there is more information in the available literature that describes results from constant temperature experiments; however, they do not accurately reflect what is typical in a natural river environment. However, there are only a few studies that successfully mimicked natural thermal conditions to determine how water temperature during early incubation may ultimately affect the survival of Chinook salmon fry in a natural environment. These various studies, when synthesized, also indicate that the ultimate incubation survival of Chinook salmon embryos is not affected only by a specific temperature, but more importantly, survival is directly related to the length of time that embryos are exposed to elevated thermal conditions. With respect to fry size at emergence, most all data that indicates warmer temperature produces smaller fry is based on single observation studies that did not maintain replicates, and could not be statistically analyzed. While some researchers may still maintain that warmer incubation conditions generally produce smaller fry, it is also apparent that those fry emerge and begin feeding earlier than their cohorts exposed to cooler conditions. There is no evidence that earlier emerging fry are subjected to a reduced survival advantage. In fact it has been postulated that early emergence and feeding may provide a distinct territorial and growth/survival advantage.

To assess the thermal requirements for incubating fall Chinook salmon in a riverine environment, three of the studies reviewed provide the most complete information. Olson and Foster (1955), Olson et al. (1970), and Geist et al. (2006) provide objective mortality data for fall-run Chinook salmon based on temperature treatments that mimicked natural conditions. The data from these three studies were compiled, and a database developed that relates the ultimate fry mortality of each egg lot to the highest temperature they were exposed to during tests. A plot of the data reveals that mortality was relatively low through about 16.0° C, but between 16.0 and 17.0° C mortality sharply increased (Figure 14).

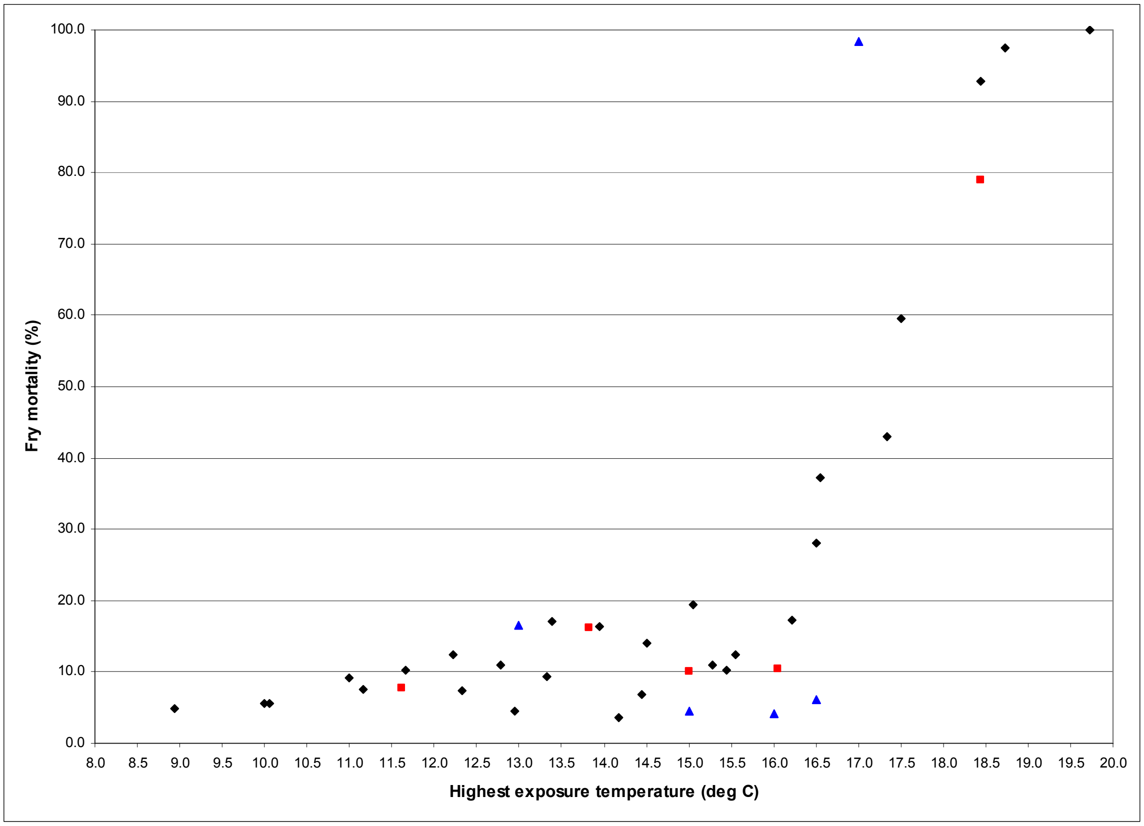

Figure 14. Final fry mortality (%) relative to the highest water temperature (ºC) that embryos were exposed to during natural/variable temperature experiments (data from Olson and Foster (1955), Olson et al. (1970), and Geist et al. (2006)).

The data was further placed into categories that would allow for statistical analysis. As an example, all mortality data that resulted from a highest exposure temperature between 12.6 and 13.5° C were placed in a group represented by 13.0° C. This was done for six temperature categories including 12.0, 13.0, 14.0, 15.0, 16.0, and 17.0° C. Two other groups were made, for 10.0 and 19.0° C, and included all mortality data that resulted from highest exposure temperatures less than 11.6 and greater than 17.5° C, respectively. After the data were assigned to specific groups, the mean mortality was calculated for each thermal category and plotted that data along with the estimated 95% upper and lower confidence interval (Figure 15).

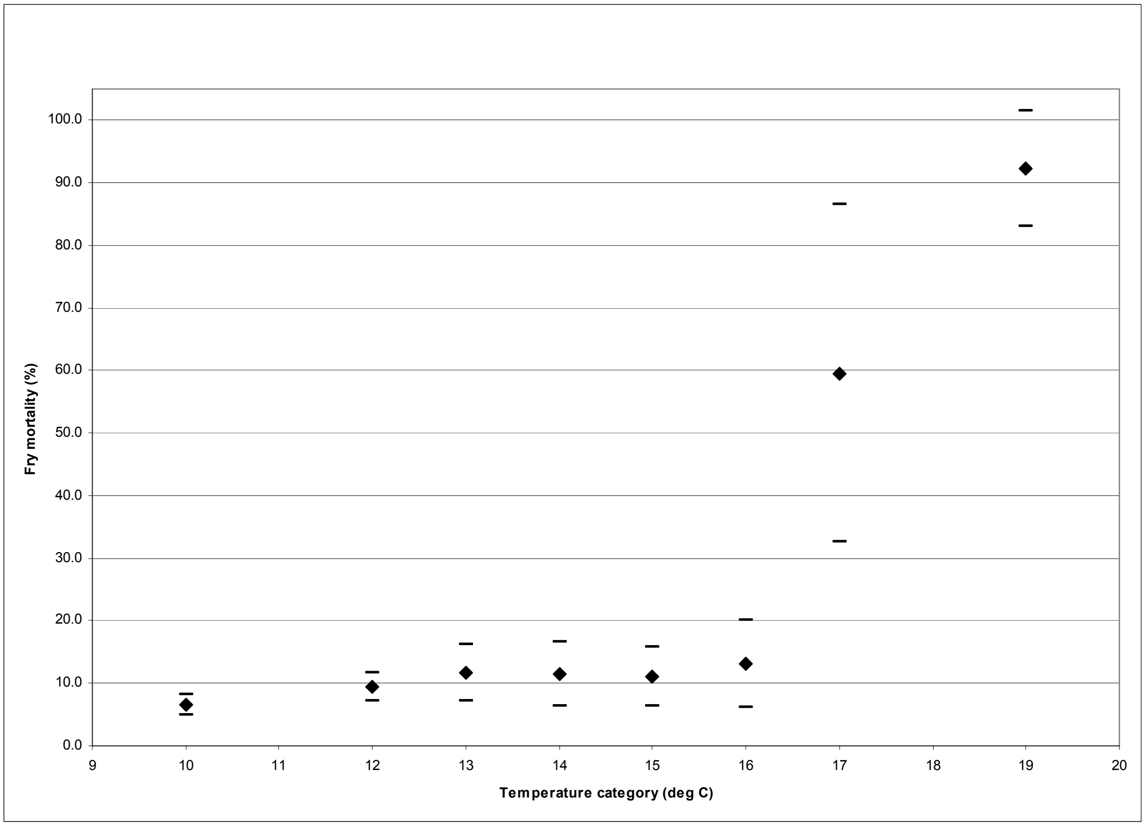

Figure 15. Mean fry mortality (with 95% confidence interval) within thermal exposure categories

It becomes apparent that the mean mortality data was low and similar across all thermal exposure categories, 10.0 through 16.0° C. However, the categories represented by 17.0 and 19.0° C had very high and more variable mortality. The data for each temperature exposure category was finally tested using a series of t-tests (α =0.05) against all other data in order to determine if a statistical difference existed among the various categories. The results are shown in Table 7, and confirm that mortality is statistically similar among all of the temperature exposure categories from 10.0 through 16.0° C, and that while the categories representative of mortality at 17.0 and 19.0° C are statistically similar to each other, those data indicate that mortality at those temperatures is significantly greater than at all lower temperatures.

Table 7. T-test matrix showing the P-value calculated from comparing the mean mortality values between each temperature exposure category. Significant values (P≤0.05) are in bold and are italicized; highly significant values (P≤0.01) are in bold, italicized, and underlined.

Temperature exposure categories (with sample size)								
	10.0 n=5	12.0 n=4	13.0 n=5	14.0 n=5	15.0 n=5	16.0 n=6	17.0 n=4	19.0 n=4
10.0		0.0901	0.0907	0.1354	0.1338	0.1254	***0.0307***	***<u><0.01</u>***
12.0	0.0901		0.4153	0.5120	0.5635	0.3622	***0.0353***	***<u><0.01</u>***
13.0	0.0907	0.4153		0.9355	0.8476	0.7506	***0.0383***	***<u><0.01</u>***
14.0	0.1354	0.5120	0.9355		0.9190	0.7105	***0.0373***	***<u><0.01</u>***
15.0	0.1338	0.5635	0.8476	0.9190		0.6426	***0.0369***	***<u><0.01</u>***
16.0	0.1254	0.3622	0.7506	0.7105	0.6426		***0.0392***	***<u><0.01</u>***
17.0	***0.0307***	***0.0353***	***0.0383***	***0.0373***	***0.0369***	***0.0392***		0.0929
19.0	***<u><0.01</u>***	***<u><0.01</u>***	***<u><0.01</u>***	***<u><0.01</u>***	***<u><0.01</u>***	***<u><0.01</u>***	0.0929	

The data from these three studies are very consistent and are likely the best information that can be used to describe how fall-run Chinook salmon embryo incubation mortality can be affected by temperatures characterized by a naturally varying thermal regime. They all used similar stocks of fall-run Chinook salmon, and conducted exposure tests in a similar, repeatable manner. They all had very similar results. The data were compiled and analyzed based on the highest temperature experienced by test organisms. This was done because as the data were being reviewed, it was obvious that even though tests were designed so that the initial exposure temperature would be the highest, this was not always the case. Because of natural variability experienced in the Olson et al. (1970) study, the highest temperature within each treatment occurred a few days after the experiment had begun. However, if the initial test temperatures were used, the results are the same. Constant temperature exposure tests are not representative of conditions found in a natural environment, and tend to indicate that when water temperature is higher than about 13.0° C, then extensive mortality would be expected to occur during incubation. However, by using data from naturally varying exposure tests, it appears more reasonable that when incubating embryos are subjected to an early elevated temperature as high as 16.0° C, and that their exposure is to a normal declining thermal regime, they should not be expected to experience abnormal/excessive levels of mortality. This information is more realistic than results and recommendations based on constant temperature exposure tests. This type of information also makes it evident that it should be possible to develop a realistic site-specific spawning/incubation temperature criteria for the Snake River fall Chinook salmon.

Based on these studies, it is the conclusion of IPC that the thermal shift created by Hells Canyon Complex has had very little adverse impact on the success of incubation survival for those redds spawned at initial temperatures of between 16 ºC to 16.5 ºC. These redds do not experience different levels of mortality from those eggs spawned at temperatures as low as 13 ºC. At temperatures above 16.5 ºC, mortality of incubating embryos substantially increases. In the upper Hells Canyon Reach, temperatures can be above 16.0 ºC on average between October 10 and October 18. This suggests that redds constructed during this time period may have lower survival than redds constructed after this time period. Redds constructed after this period have equal probability of survival regardless of the temperature at which they were constructed. This suggests that less than 2% of redds in an average spawning distribution would be affected by elevated temperatures (Chandler et al. 2001). Although the thermal shift that occurs below Hells Canyon Dam delays cooling of water temperature in the fall it significantly advances the emergence timing of juvenile fall Chinook salmon, closer to what occurred historically in the primary production areas upstream of the Hells Canyon Complex.

4.7 Effects of Intragravel Water Temperature

There has been concern expressed by some that water column metrics to evaluate the thermal effects on incubating fall Chinook salmon may not be representative of actual intergravel (inter-redd) temperature conditions. For example, past reports (e.g. Geist et al. 1999, Hanrahan et al. 2004) have indicated that water temperature within the intragravel environment (where Chinook salmon embryos incubate) is roughly 2-3°C warmer than conditions in the water column throughout the incubation period. A difference of this magnitude would be of significant concern, especially when evaluating site specific fall Chinook salmon spawning water quality criteria that is based on water column conditions, and does not take into account what might be present in the intragravel incubation environment. However, these reports should be put in proper context. Also, there is more recent data that can help researchers, managers, and regulators to better understand this thermal difference between the two environments.

Early data collected by Geist et al. (1999) and Hanrahan et al. (2004) came from measurements obtained from piezometers installed into the ambient shallow and deep hyporheic environment (as deep as 150 cm) into the undisturbed gravel substrate. While these data were collected in gravel areas where Chinook salmon would normally be expected to spawn, the data presented in those reports do not represent thermal conditions present in Chinook salmon redds.

The thermal environment within Chinook salmon redds can be strongly influenced by surface water conditions (Geist et al. *In press*). Modification of the substrate composition during redd construction alters the local hydraulics and permeability of the shallow hyporheic zone, and allows for a high degree of exchange between the surface water and the inter-redd environment (Burner 1951; Vronskiy 1972; Chapman 1988; Hanrahan 2007). Chinook salmon also tend to spawn where the natural down-welling of surface water into the shallow hyporheic zone occurs (Vronskiy 1972; Leman 1988; Vronskiy and Leman 1991; Geist 2000; Geist et al. 2002; Hanrahan et al. 2004). The use of predominantly down-welling spawning habitats by Chinook salmon contrasts with other Pacific salmon species, such as chum (*O. keta*), sockeye (*O. nerka*), and coho (*O. kisutch*), which tend to spawn in areas that have strong up-welling conditions, and can experience larger thermal gradients between surface water and the shallow hyporheic zone (Tautz and Groot 1975; Leman 1988; Geist et al. 2002). Redistribution of the substrate and reduction of fine material during redd construction, and the disposition to spawn in a naturally down-welling environment, facilitate increased interaction between surface water and the incubation environment within Chinook salmon redds. This can result in physicochemical similarities between surface waters and the inter-redd environment, specifically with relation to temperature. This similarity makes it feasible to use surface water temperature data as a reliable surrogate for describing the thermal environment that Chinook salmon embryos experience during incubation.

The thermal environment within a Chinook salmon redd in a large river can be more variable than surface water conditions, especially as the incubation season progresses following redd construction and deposition of eggs. However, in the Snake River, temperature within the redd environment is generally the same as what is present in the water column, especially during the first few weeks following redd construction. Similar findings have been reported by Ringler and Hall (1975), Vronskiy and Leman (1991), Hanrahan et al. (2004), and Hanrahan (2007), which were based on data collected from artificial redds. The following eight graphs depict the mean water column and inter-redd temperatures (for redds constructed in early November 2004 and 2005) measured at sites studied in the upper Hells Canyon of the Snake River (Figures 16 through 23 . Note that if it is difficult to discern the lines differentiating the water column and the inter-redd environment, that is because they fall directly on top of each other.

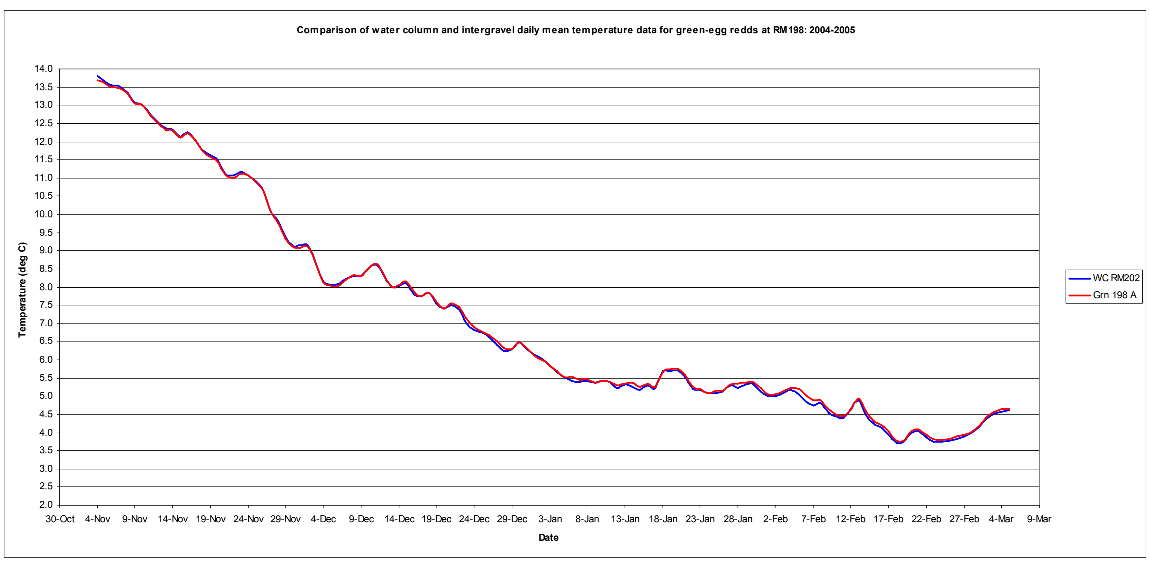

Figure 16. Comparison of water column and inter-redd environment water temperatures at simulated redd sites at RM 198 during the years 2004-2005.

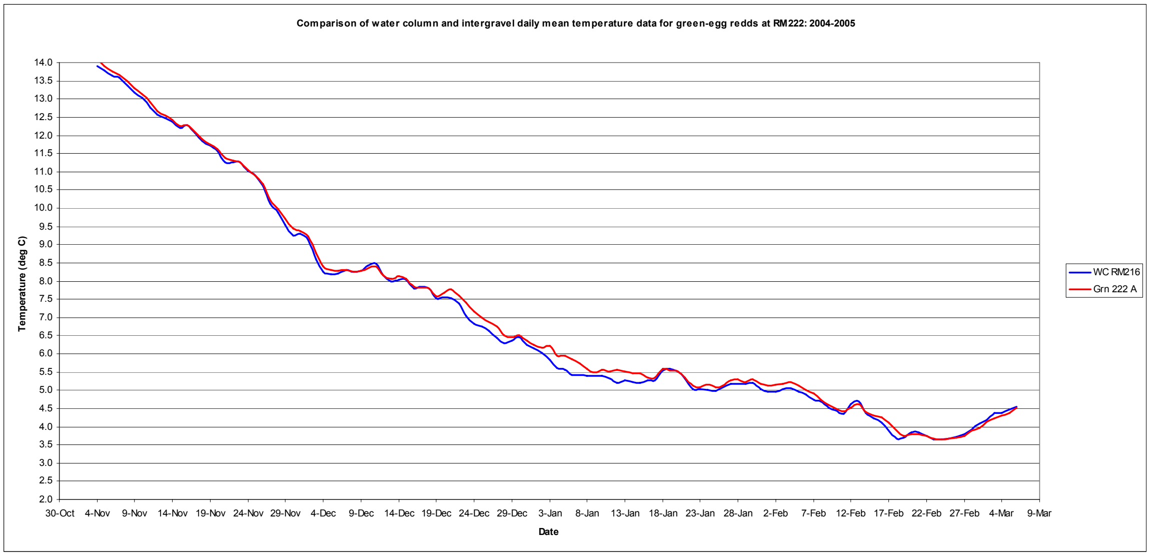

Figure 17. Comparison of water column and inter-redd environment water temperatures at simulated redd sites at RM 222 during the years 2004-2005.

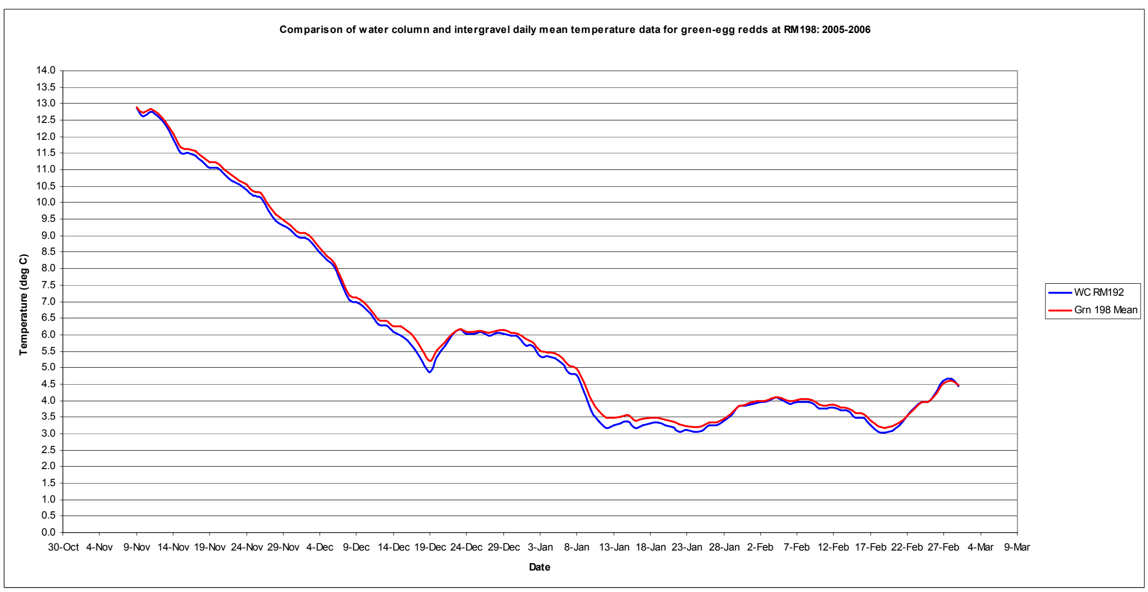

Figure 18. Comparison of water column and inter-redd environment water temperatures at simulated redd sites at RM 198 during the years 2005-2006.

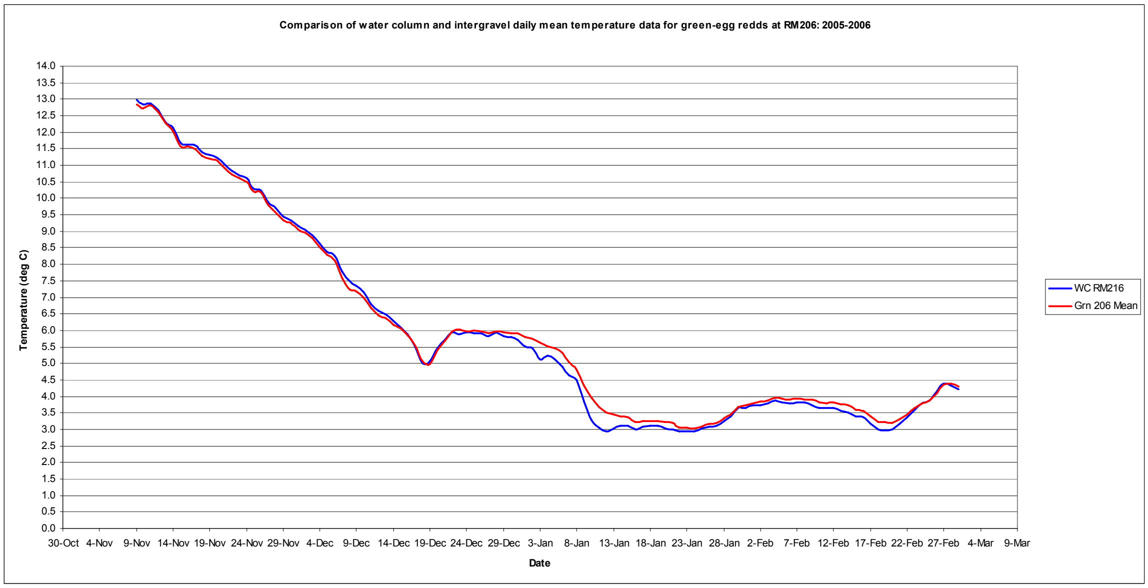

Figure 19. Comparison of water column and inter-redd environment water temperatures at simulated redd sites at RM 206 during the years 2005-2006.

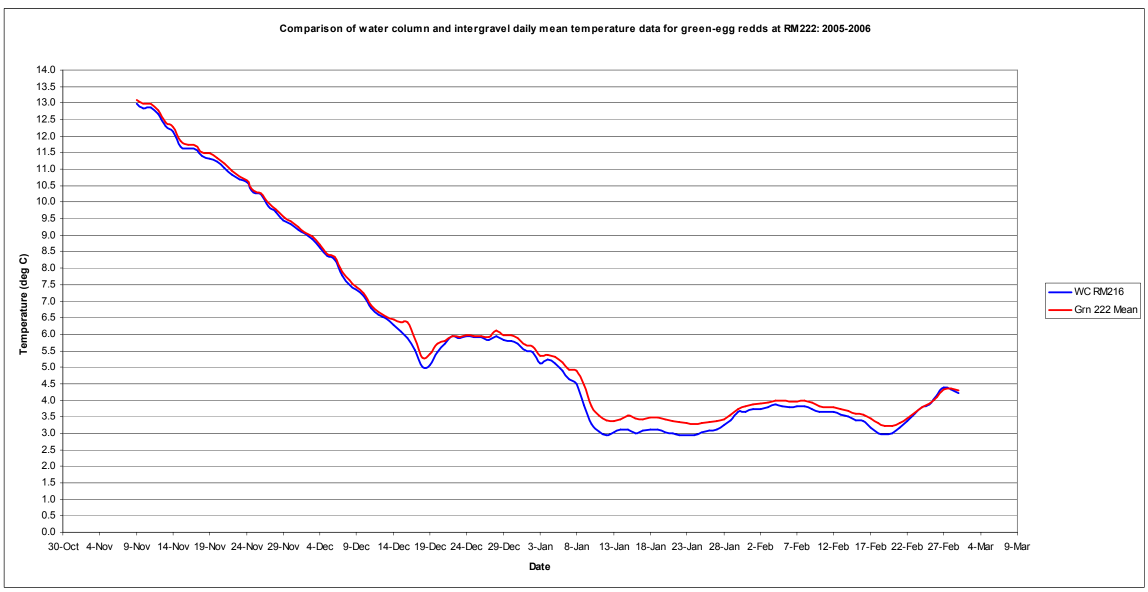

Figure 20. Comparison of water column and inter-redd environment water temperatures at simulated redd sites at RM 222 during the years 2005-2006.

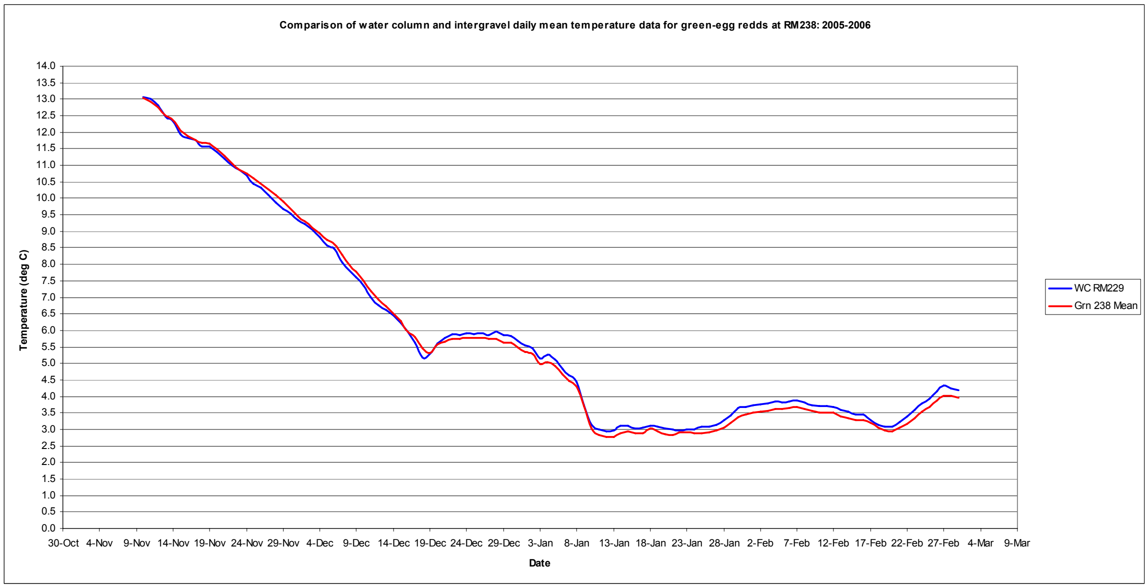

Figure 21. Comparison of water column and inter-redd environment water temperatures at simulated redd sites at RM 238 during the years 2005-2006.

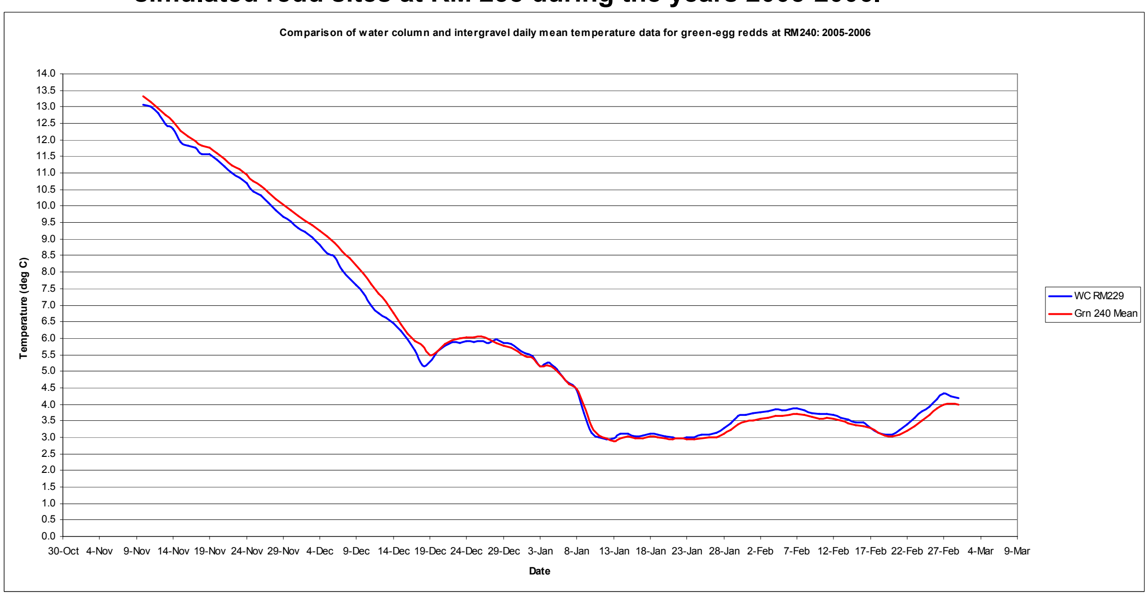

Figure 22. Comparison of water column and inter-redd environment water temperatures at simulated redd sites at RM 240 during the years 2005-2006.

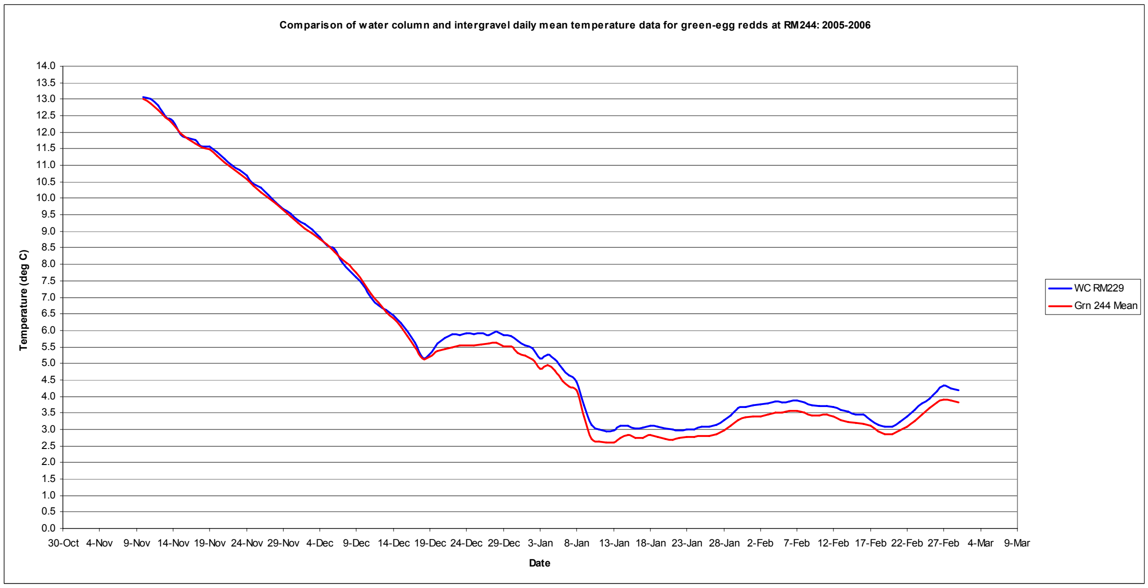

Figure 23. Comparison of water column and inter-redd environment water temperatures at simulated redd sites at RM 244 during the years 2005-2006.

These data clearly show that for approximately five weeks post construction the water temperature within a redd remains virtually identical to what is present within the water column. Furthermore, for individual artificial redds constructed in the upper Hells Canyon Reach during 2004 and 2005, the maximum temperature difference between the inter-redd environment and the water column, during the first five weeks following construction, was only 0.5°C, and averaged 0.1°C. As well, ***throughout the entire incubation period***, the water temperature within individual redds tended to remain within approximately 0.5°C of what was measured in the water column.

4.8 Low Dissolved Oxygen and Water Temperature

The influence that water temperature may have on various life stages could be influenced by low levels of dissolved oxygen in the water adding a potential stressor. Often, laboratory studies relative to optimal temperature determinations are conducted under optimal dissolved oxygen levels, thus their application to the environmental condition being experienced by the particular life stage of fish may be limited. By late-August dissolved oxygen levels below Hells Canyon Dam are at their lowest, generally around 4.5 mg/L. Dissolved oxygen tends to remain at this low level through about the beginning of October, when it begins to increase rapidly, reaching levels generally ≥6.0 mg/L during the last week of October. While these levels are low, it should be understood that as water progresses downstream through the upper Hells Canyon Reach, it flows through a series of high gradient, turbulent rapids, which effectively increase the dissolved oxygen levels by about 2.0 mg/L by the time it reaches RM 238 (nine miles downstream of the Hells Canyon Dam), just downstream of Granite Rapids. In effect, any potential negative effects that may occur due to an interaction of increased water temperature and low dissolved oxygen would likely be restricted to that uppermost nine miles of the upper Hells Canyon Reach, during the earliest portion of the spawning period.

With respect to migrating adults, it is conceivable that fall Chinook salmon might be blocked from entering the most upstream nine miles of the Snake River spawning habitat during late-August through late-September when dissolved oxygen levels are at their lowest, and water temperatures can be between 19-22°C. However, after early to mid-October, dissolved oxygen levels are increasing above 4.5 mg/L, while water temperatures are quickly declining below 19.0°C. This would reduce the potential for a migration block into that upper nine miles of river by mid- to late-October, and would also reduce the potential for negative effects to occur to fertilized embryos.

It is also important to understand that during the past 16 years of spawning surveys below Hells Canyon Dam, only a very limited number of redds have been observed being constructed in the uppermost nine miles of the upper Hells Canyon Reach prior to the third week of October. Only during three of those years were redds observed prior to 21 October, and they amounted to 0.3% of the total spawning observed in the mainstem Snake River in those years.

Geist et al. (2006) evaluated the effects of low dissolved oxygen levels under different thermal conditions. Their various treatments included five initial temperatures of 13.0, 15.0, 16.0, 16.5, and 17.0° C, coupled with four initial dissolved oxygen levels of 4.0, 6.0, 8.0 mg/L or 100% saturation. Test organisms in the temperature groups of 13.0 and 17.0° C were only exposed to 100% saturation of dissolved oxygen. Each temperature group had a declining thermal regime equal to 0.2° C per day through the first 40 days of the tests. After day 40, all treatments were thereafter exposed to a normal Snake River temperature regime as described by the mean daily water temperature of the upper Hells Canyon Reach among the years 1991-2003. As well, initial dissolved oxygen levels were maintained through the first 16 days, whereupon they were then increased by 2.0 mg/L. On day 39 they were again increased by 2.0 mg/L, and after day 40 they were maintained at 100% saturation. The authors reported that survival of developing embryos was linked only to temperature. The authors reported that development timing was accelerated at higher temperature, and at higher dissolved oxygen levels (see Table 3 in Geist et al. 2006). Again, this information comports well with what other, earlier researchers have reported. Lower dissolved oxygen tended to result in an increase in abnormalities. Groups initially held at 4.0 mg/L dissolved oxygen generally had twice as many abnormalities as groups started at higher levels; however, this was still a very small proportion of any group (≤6.0%), and there was no statistical difference among groups. Finally, the growth of embryos was only very slightly affected by differences in temperature and dissolved oxygen. The wet weight at hatch, as well as the wet weight and fork length at emergence were statistically similar among all groups. While the fork length of alevins at hatch differed among treatments, the largest difference was only 1.0 mm; it is difficult to infer that this difference would have a profound effect on later survival, especially since at emergence this difference no longer existed. The most important difference that was observed, with respect to growth, was that yolk conversion efficiency tended to be better in embryos initially exposed to higher dissolved oxygen levels. At emergence, the dry weight of fry was not different among treatment groups; however, the amount of yolk was significantly less in groups that were initially exposed to 100% saturation of dissolved oxygen.

4.9 Growth of Juvenile Fall Chinook Salmon

Thus far, the analysis of temperature has focused primarily on effects of survival or fitness of fall Chinook salmon. Another aspect of temperature is how it may affect growth, which may have both direct and indirect effects on survival. In earlier sections, growth and development of incubating embryos relative to temperature was discussed. For returning adults, growth relative to water temperature is not a relevant issue because adult fall Chinook salmon are not feeding or experiencing somatic growth. Growth in adult fall Chinook salmon is relevant primarily to the development and viability of gametes, which was discussed in earlier sections. This leaves the consideration of growth of rearing juvenile fall Chinook salmon relative to temperature and the effects of the thermal shift below Hells Canyon Dam. Juvenile Chinook salmon, including fall Chinook, that rear in the Snake River exhibit exceptional growth. Juvenile fall Chinook below Hells Canyon Dam exhibit rapid growth by comparison with those of other ocean type fall Chinook salmon populations and are equal to, or better than, growth rates reported for productive brackish and saltwater habitats along the Pacific coast of North America.

Connor and Burge (2003) note that fry of Snake River fall Chinook salmon rearing downstream of the Hells Canyon Dam (in different river reaches) grow at different rates. Based on recapture of PIT-tagged fry within each reach, they estimated that fry in the upper contemporary reach grow at approximately 1.2 mm/day, and fry in the lower reach grow at approximately 1.0 mm/day. Based on the way they calculated these growth rates, they then speculated that fry in the historic Marsing Reach may have grown at a slightly greater rate, 1.4 mm/day.

IPC evaluated potential growth rates using a different approach than that of Connor and Burge (2003). Rather than establishing an index period to calculate mean water temperature of each reach (March 20 through June 20), IPC, using the same data-set with the inclusion of four additional years, developed a growth model as a function of local water temperature (Figure 24). This data set includes PIT-tagged fish from both the upper and lower reaches of the Snake River downstream of the Hells Canyon Dam. IPC calculated increments of growth in fork length of PIT-tagged fish that were captured and recaptured in local areas over short periods (less than 10 days). IPC used thermal data from each reach, over the same capture-recapture periods, to define a thermal exposure condition (in one degree Celsius increments) that was relevant to the growth period. In agreement with other researchers, this model indicates that growth of rearing fall Chinook salmon fry tended to increase from 10°C through about 17°C, and thereafter declines (Banks et al. 1971; Marine 1997; Connor et al. 2002; Connor and Burge 2003 Connor et al. 2003). Historically, for the Marsing and the upper Hells Canyon reaches prior to the construction of the HCC, water temperature began to exceed 17.0°C by about the end of May. Water temperatures in the mainstem Snake River presently exceed 17.0°C upstream and downstream of the Salmon River confluence by about 18 and 26 June, respectively, thus extending suitable growth conditions longer than what occurred historically. As discussed in the next section, juvenile sub-yearling originating from the mainstem Snake River downstream of Hells Canyon Dam tend to be more than 95% evacuated from their natal rearing areas by early June .

Based on this review, it is the conclusion of IPC that the thermal shift below the Hells Canyon Complex has not had an adverse effect on growth of juvenile fall Chinook salmon, and has extended suitable growing conditions.

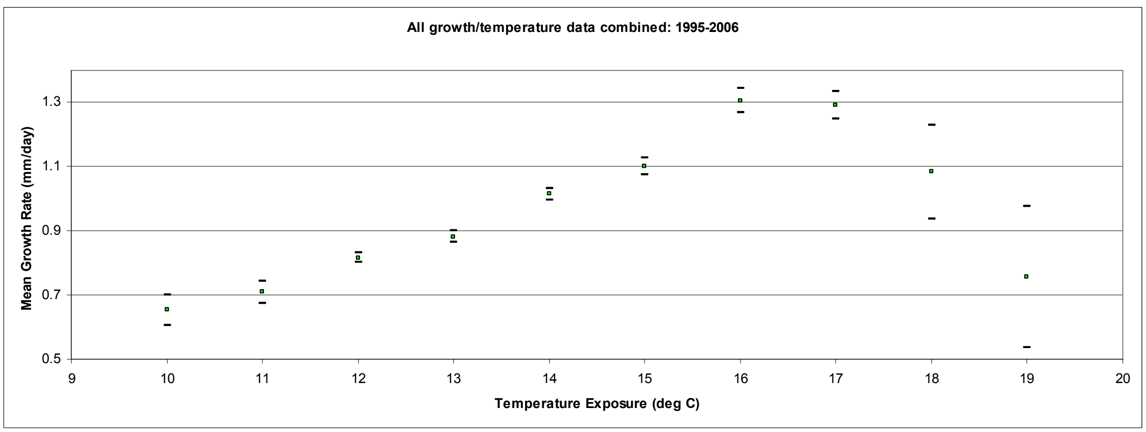

Figure 24. Mean growth rate of fall Chinook salmon fry rearing within the Snake River downstream of the Hells Canyon Dam, as a function of exposure to local water temperature conditions. The bars above and below each data point are the 95% confidence interval associated with each exposure temperature. Data was compiled from pit-tagged captures and recaptures within local rearing areas of the Snake River over periods of 10 days or less, for the spring seasons 1995 through 2003 (raw PIT tag capture and recapture data collected by the USFWS and made available through DART website).

4.10 Outmigration Timing

The potential effect of growth and development timing of juvenile fall Chinook salmon as a result of the temperature shift below Hells Canyon Dam may strongly influence the timing of the outmigration of juvenile fall Chinook salmon. This is a concern because it has been demonstrated that later migrating fall Chinook salmon juveniles experience lower survival to Lower Granite Dam than do earlier migrants (Connor et al. 2002). The thermal shift observed below Hells Canyon Dam is often identified as a causal factor in delayed migration timing as to when fall Chinook salmon migrate past Lower Granite Dam. The comparison of historic passage timing of sub-yearling Chinook salmon emigrants past the Central Ferry location on the Snake River (roughly 25 miles downstream of the present-day Lower Granite Dam), and the later contemporary passage timing of similarly aged fall Chinook salmon juveniles at Lower Granite Dam is often used as “evidence” of a shift in emergence timing, which is claimed to cause delayed rearing and emigration. In the recent past, up to 50% of the subyearling smolts from the upper reach of the Snake River passed Lower Granite Dam by early July, whereas historically it was believed that they were completely out of this reach by the end of June. This apparent delay in emigration is often attributed to later emergence timing than to what is believed to have occurred historically when production was in the Swan Falls Reach.

A more meaningful comparison relative to the effect of the HCC on emergence and emigration timing is to compare pre-Hells Canyon Complex temperatures of Hells Canyon to present day temperature of Hells Canyon. This comparison indicates that the Hells Canyon Complex warmed the incubation environment such that emergence timing today in Hells Canyon is much earlier relative to what it was pre-HCC. Further, post-HCC temperatures are much closer present-day to the historic Swan Falls spawning area. This suggests that construction of the HCC made the thermal regime of the Hells Canyon area more conducive to spawning incubation and early survival present-day than it was pre-HCC. In fact, Connor et al. (2002, 2005) support the proposition that the upper Hells Canyon Reach, the reach most closely influenced by the HCC, fosters an “ocean type” life history, whereas other reaches such as the Clearwater have significant delays in emergence relative to what occurred historically in the Swan Falls reach.

It is also interesting to note that migration timing of fish arriving at Lower Granite Reservoir is shifting earlier in more recent years. However, this shift to earlier emigration cannot be tied to the HCC, as the thermal regime and emergence timing has not shifted recently. This suggests that other factors beyond emergence timing strongly influence the timing of migration at Lower Granite Dam.

The following table (Table 8) is based on available passage data at Lower Granite Dam of juvenile pit-tag fall Chinook salmon originating from the mainstem Snake River (above and below the confluence with the Salmon River), as well as the overall Smolt Passage Index (SPI). The SPI includes naturally produced juveniles from the mainstem Snake River as well as the Clearwater, Grande Ronde, Salmon, and Imnaha rivers, in addition to all hatchery fish released at several locations throughout the Snake and Clearwater rivers. These data are publicly available through both the DART and PITAGIS web pages.

Table 8. Date of 50% and 90% passage at Lower Granite Dam for Age-0 wild fall Chinook salmon and also the date of Smolt Passage Index (SPI) for those percentages for the years 1995 and 2006.

Year	Date of 50% FaCH 0 Passage			Date of 90% FaCH 0 Passage		
	SPI	Wild FaCH Above	Wild FaCH Below	SPI	Wild FaCH Above	Wild FaCH Below
1995	30 Jul	20 Jul	30 Jul	20 Sep	18 Aug	04 Sep
1996	19 Jul	04 Jul	18 Jul	25 Aug	18 Jul	11 Aug
1997	15 Jul	11 Jul	13 Jul	16 Sep	05 Aug	08 Aug
1998	13 Jul	07 Jul	11 Jul	22 Aug	17 Jul	30 Jul
1999	03 Jul	04 Jul	25 Jul	15 Aug	31 Jul	15 Aug
2000	02 Jul	27 Jun	02 Jul	15 Aug	04 Jul	08 Aug
2001	03 Jul	No Data	06 Jul	07 Aug	No Data	03 Aug
2002	08 Jul	01 Jul	06 Jul	31 Jul	19 Jul	22 Jul
2003	18 Jun	25 Jun	29 Jun	12 Jul	10 Jul	12 Jul
2004	21 Jun	23 Jun	24 Jun	13 Jul	03 Jul	06 Jul
2005	03 Jun	11 Jun	15 Jun	19 Jun	23 Jun	29 Jun
2006	05 Jun	13 Jun	26 Jun	02 Jul	28 Jun	04 Jul

For data covering 1995-2006, the mean dates of 50% and 90% passage of wild fall Chinook salmon juveniles originating in the Snake River upstream of the Salmon River confluence at Lower Granite Dam are 30 June and 16 July, respectively. Note that the dates of 50% and 90% passage at Lower Granite Dam are becoming earlier.

Juvenile fall Chinook salmon growth tends to become reduced at temperatures >17.0°C. Water temperatures in the mainstem Snake River presently exceed 17.0°C upstream and downstream of the Salmon River confluence by about 18 and 26 June, respectively. Historically, these river reaches likely exceeded 17.0°C by about the end of May. This is approximately a two to three week difference, and the extended period of cooler conditions presently available in the river during the rearing period likely allows juvenile fish a longer opportunity for rearing.

One factor often overlooked in this assessment is that juvenile sub-yearling emigrants originating from the mainstem Snake River downstream of the Hells Canyon Dam tend to be more than 95% evacuated from their natal rearing areas by early June, and should be past Lower Granite Dam by the end of June, as was observed historically. This would be similar to the passage timing observed by Mains and Smith (1964). However, juvenile fall Chinook salmon originating from both the upper and lower free-flowing reaches of the Snake River must now navigate slack-water reservoirs downstream of their contemporary rearing grounds which results in delayed emigration through the lower Snake River (downstream of Lewiston, Idaho).

Fall Chinook salmon emerge earlier today in Hells Canyon than they did historically in Hells Canyon because of the warmer incubation conditions present today as a result of the HCC. Historically, Hells Canyon was a very cold environment and may not have been conducive for production of an Age-0 migrating fall Chinook salmon. The construction of the HCC altered the thermal regime such that emergence timing is now closer to what occurred historically in the production areas upstream of the HCC. During the 1990's, there was evidence that juvenile outmigration was delayed based on their arrival timing at Lower Granite Dam. Migration through the large slack water environment of Lower Granite Reservoir is more likely to explain the delay observed during that time. Recently, there is evidence of an earlier shift in the outmigration timing at Lower Granite. Fall Chinook salmon appear to be migrating earlier and at a smaller size than observed in the 1990's. Why this trend is occurring is uncertain, but may relate in some way to density in the rearing areas as adult returns and natural production has continued to increase.

5. A Summary of Conclusions

1. Significant anthropogenic influences on water temperature have occurred in the Snake River basin both upstream of Hells Canyon Dam and as a result of the Hells Canyon Complex. Generally, upstream of the Hells Canyon Complex is warmer during the spring and summer months relative to the pre-development era (pre-1860). This thermal inertia influences the magnitude and duration of the thermal shift downstream of Hells Canyon Dam that was created by the operation of the HCC.

2. The presence of the HCC has also created warmer over-winter base temperatures in the area below Hells Canyon Dam relative to the pre-development era because of the large volume of 4ºC water stored in Brownlee Reservoir over the winter months.

3. The primary effect of this altered thermal regime to the various life stages are as follows:

> *a. Adult migration* – There has been no apparent shift in adult migration timing. Adult fall Chinook salmon experience a similar period of exposure to temperatures elevated above 20 ºC between mid-August and mid-September as they did pre-HCC, but experience a lower maximum temperature than occurred historically. This is based on a comparison of current data with water temperatures present at Central Ferry in the early to mid-1950's, prior to construction of the HCC or the lower Snake River reservoirs.
>
> *b. Pre-spawn mortality* – Some level of pre-spawning mortality among anadromous salmonids is common. There is evidence that adult salmon in hatchery holding environments exposed to prolonged periods of water temperatures > 19 ºC could be subject to significant pre-spawn mortality. In hatchery holding situations, the mortality is usually associated with increased susceptibility to disease. However, fish-to-redd ratios documented in the Snake

River do not suggest excessive pre-spawn mortality of fall Chinook salmon. It may be that the non-confined environment of a large river under a naturally declining thermal regime and the potential of seeking cooler refuge makes fish less susceptible to disease and mortality. In addition, HCC operations cools late summer outflows relative to temperature levels associated with inflow and the operations of Dworshak Reservoir substantially cool areas associated with Lower Granite Reservoir and create thermal refugia during the early pre-spawn environment such that conditions prevalent today are better than conditions prior to the HCC.

c. Gamete viability – A through review of the literature demonstrates that studies often cited to suggest reduced gamete viability as a result of prolonged exposure to warmer temperatures should not be cited as supporting literature. The studies typically were not designed to address the question. One study that could be cited as supporting evidence (Jensen et al. 2006) did not hold adult Chinook salmon in a declining thermal regime typical of a riverine environment, but rather exemplified relatively long-term (40-days) exposure to elevated water temperatures. In addition, the control group held fish in a constant thermal environment of between 8 and 9 ºC, which cannot be compared to a declining thermal regime under more normative environments. Based on the available information for this topic, it is difficult to conclude that the HCC has had an adverse effect on development of gametes in returning adult fall Chinook salmon.

d. Disease susceptibility – Similar to the findings discussed under Pre-spawn mortality, adults held in confined hatchery environments under prolonged periods of elevated temperature appear to have a greater susceptibility to disease or fungal infections. How this pertains to free-ranging adults is uncertain. However as discussed above, fish to redd ratios do not suggest a high level of pre-spawn mortality below Hells Canyon Dam.

e. Spawn timing – There is no evidence that spawn timing has been greatly altered in the Snake River when comparing pre-HCC spawn distribution to that of the present-day Hells Canyon spawn distribution.

f. Incubation Survival – Experiments based on constant and declining thermal regimes differ markedly in their results with respect to both ultimate survival and size of fry at emergence. To assess the thermal requirements of incubating eggs in a natural declining thermal regime, Olson and Foster (1955), Olson et al. (1970) and Geist et al. (2006) are the most applicable findings to conditions experienced by Snake River fall Chinook salmon. These studies suggest that eggs spawned at initial temperatures of between 16 ºC to16.5 ºC do not experience different levels of mortality from those eggs spawned at temperatures as low as 13 ºC. At temperatures above 16.5 ºC, mortality of incubating embryos substantially increases. The thermal shift that occurs below Hells Canyon Dam delays cooling of water temperature in the fall and significantly advances the emergence timing of juvenile fall Chinook salmon closer to what occurred historically in the primary production areas upstream of the HCC. The Hells Canyon Reach is now more suitable for the expression of an Age-0 fall Chinook salmon life history than it was before construction of the HCC. The elevated winter base winter temperatures also contribute to the advanced emergence timing relative to pre-HCC.

g. Effects of intragravel water temperature – In Hells Canyon, there is a strong connection between the water column and the redd environment that allows for similar thermal conditions between the two environments. Therefore, the water column conditions provide good metrics for describing the thermal conditions of incubating embryos in Hells Canyon.

h. Emergence / Outmigration Timing - Fall Chinook salmon emerge earlier today in Hells Canyon than they did historically in Hells Canyon because of the warmer incubation conditions present today as a result of the HCC. Historically, Hells Canyon was a very cold environment and may not have been conducive to production of an Age-0 migrating fall Chinook salmon. The construction of the HCC altered the thermal regime such that emergence timing is now closer to what occurred historically in the production areas upstream of the HCC. During the 1990's, there was evidence that juvenile outmigration was delayed based on their arrival timing at Lower Granite Dam. Migration through the large slack water environment of Lower Granite Reservoir is more likely to explain the delay observed during that time. Recently, there is evidence of an earlier shift in the outmigration timing at Lower Granite. Fall Chinook salmon appear to be migrating earlier and at a smaller size than observed in the 1990's. Why this trend is occurring is uncertain, but may relate in some way to density in the rearing areas as adult returns and natural production has continued to increase.

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